Mapping Priority Marine Habitats: Knowledge of their Ecosystem to Underpin the Marine Planning Process

Kate Sarah Geddes Gormley

A thesis submitted for the degree of
Doctor of Philosophy

School of the Built Environment
and School of Life Sciences

Heriot-Watt University, Edinburgh

March 2014

Abstract

Marine planners need to know about ecosystems, such as Priority Marine Habitats (PMHs) in order to manage and conserve them effectively. The overarching theme of this thesis is to contribute to this knowledge through the development of "marine planning tools". The primary focus is on the PMH, *Modiolus modiolus* beds, although other PMHs and Marine Protected Areas (MPAs) were also considered. Four key studies were designed and conducted, i) Species Distribution Modelling (SDM) of *M. modiolus* in UK waters; ii) SDM of PMHs in Europe; iii) assessment of MPA management effort; and iv) the genetic connectivity of *M. modiolus* beds

Overall, the research provided information and knowledge to contribute to implementation of a truly ecosystem-based approach to management and effective PMH management. It is now known: i) where *Modiolus modiolus* beds occur; ii) where they have the potential to occur, now and in the future; iii) that there is the potential for them to be lost/ hindered or lack-viability if ocean temperatures increase; iv) that they may become more important to conservation at northern latitudes in the future; v) that European nations will have to work towards integrated marine conservation policies and protection when considering all PMHs; vi) that some MPAs may require more effort to manage than others and that it may be possible to predict which ones they will be; vii) that cumulative human impacts may not be the driving force for management effort; and viii) that some *M. modiolus* beds in the UK are potentially connected. The data and discussion points generated within this thesis will enable effective PMH management through the selection of appropriate management strategies.

Acknowledgements

Foremost, I would like to express my thanks and sincere gratitude to my primary supervisors Prof. Angela Hull and Dr. Joanne Porter for their continued support and encouragement over the last 3 years. Thanks to you both for your insightful comments and discussions, in particular, thanks for the motivation, patience and reassurance when things were not running so smoothly. Angela, your comments have been particularly helpful and inspiring; and Jo, thanks for all your help in the lab, I may not be as scared of molecular science as I first thought – thanks for the much needed push back into the lab!

I would also like to extend my sincere thanks to my other 'supervisors' and paper co-authors Dr. Bill Sanderson and Dr. Mike Bell. Bill, thanks for the all the time you were able to spend with me discussing my studies. Mike - thanks for introducing me to the models and for helping me develop them further; and thank you both for the time you spent commenting on my work, I have learned a lot.

I would also like to thank Dr. Mike Winson for helping me in the lab and for your patience when I needed molecular biology explained. Thank you also to Dr. Ian Davies, Marine Scotland and Dr. Douglas Watson, Scottish Power for allowing me time to discuss initial thesis ideas with you, it was a great help.

Thanks to everyone who has contributed with comments, data or analysis: in particular thank you Dr. Ilaria Coscia, University of Leuven, your microsatellite knowledge was instrumental and your patience and comments have been vital (best of luck with your new arrival); Dr. Andrew Cassidy, Dundee University, thank you for the time you spent on our samples, and for helping with the data analysis, you are a lifesaver; and Dr. Peter Robins, Bangor University, thanks for running your larval dispersal models with our data, it provided some interesting insights.

I am indebted to the Heriot Watt Dive team (and other associated teams) - Dr. Dan Harries, Dr. Bill Sanderson, Prof. Hamish Mair, Dr. Joanne Porter, Rob Cook, Nat Hirst, Flora Kent, Sally Rouse, Jen Loxton, Dr. Rohan Holt, Charlie Lindenbaum, Dave Stirling and anyone else who I may have missed - for collecting my samples, obviously without you; Chapter 7 would not be possible. Thanks also for spending many hours and cold fingers shucking mussels, I owe you many beers! Thanks as well Rob for your amazing photos.

Thanks to Nathania Weir and Ben Bryant for helping shuck mussels and with the DNA extraction – there was light at the end of the tunnel after all.

My models wouldn't have worked without the data, so thanks to everyone who contributed. In particular, thanks for the data staff at the Flanders Research Institute for providing me with endless data requests and a special thanks to Vidar Lien, Institute of Marine Research, Norway, for your help with the current velocity data. Thanks also to Sankurie Pye (National Museum of Scotland) and Andreia Salvador (Natural History Museum) for allowing me time to collect data from the mollusc collections.

Thanks to my PhD colleagues in DB2.65 – the random chat and tea (despite a seemingly endless shortage of milk; and one kitchen showdown) over the last 2 years has been great fun! Thanks particularly to Rob (and Nat), Lauren and Kai – beer, banter, cake, Starbucks, stats advice, You Tube and moaning, you are awesome!

Many many thanks to Lauren McWhinnie, my GIS partner in crime, co-conspirator, data chum, conference companion and most importantly my good friend – I doubt I would have made it to the end of my thesis in one piece if I didn't have you! Can we still meet for 9am hot chocolate when we are back at work?! Also thanks for introducing me to your supervisor – thank you Dr. Rob Briers, Napier University, for helping with some particularly tricky GIS issues.

To Euna (Mackessel, nee Macdonald; and Tom), my best friend – thank you – your wedding in Vegas was the perfect distraction at the end of a particularly tough stretch, and a great motivator to get my draft chapters written - glad we could be there to celebrate with you.

Thanks to my family for your continued support and encouragement throughout this PhD and in general; in particular my Granny (Jean) who always supports my academic career with such enthusiasm.

Finally, to my husband and all round PhD champion Fraser, thank you! If changing jobs and moving to Edinburgh so I could do this PhD was not enough, your endless support and understanding has pushed me to the end, despite the bumps along the way – I'd be lost without you (and Rocco of course – woof!)

Declaration Statement

ACADEMIC REGISTRY
Research Thesis Submission

Name*:*	**Kate Sarah Geddes Gormley**		
School/PGI:	**School of the Built Environment**		
Version: *(i.e. First, Resubmission, Final)*	**Final**	Degree Sought (Award **and** Subject area)	**Doctor of Philosophy**

Declaration

In accordance with the appropriate regulations I hereby submit my thesis and I declare that:

1) the thesis embodies the results of my own work and has been composed by myself
2) where appropriate, I have made acknowledgement of the work of others and have made reference to work carried out in collaboration with other persons
3) the thesis is the correct version of the thesis for submission and is the same version as any electronic versions submitted*.
4) my thesis for the award referred to, deposited in the Heriot-Watt University Library, should be made available for loan or photocopying and be available via the Institutional Repository, subject to such conditions as the Librarian may require
5) I understand that as a student of the University I am required to abide by the Regulations of the University and to conform to its discipline.

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Submitted By *(name in capitals):*	
Signature of Individual Submitting:	
Date Submitted:	

For Completion in the Student Service Centre (SSC)

Received in the SSC by *(name in capitals):*			
Method of Submission *(Handed in to SSC; posted through internal/external mail):*			
E-thesis Submitted *(mandatory for final theses)*			
Signature:		Date:	

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Publication List

Gormley, K.S.G., Porter, J.S., Bell, M.C., Hull, A.D. and Sanderson, W.G. (2013) Predictive Habitat Modelling as a Tool to Assess the Change in Distribution and Extent of an OSPAR Priority Habitat under an Increased Ocean Temperature Scenario: Consequences for Marine Protected Area Networks and Management. PLOS One 8(7): e68263. doi:10.1371/journal.pone.0068263

Gormley, K.S.G., Porter, J.S., Bell, M.C., Hull, A.D. and Sanderson, W.G. (2014) Distribution and Potential Change to European Priority Marine Habitats and "Conservation Hotspots": Adaptive Management to Enhance Future International Co-operation and Planning. (PLOS One: minor revisions required – March 2014)

Lauren Mcwhinnie, **Kate Gormley**, Robert A. Briers, Joanne Porter, Angela Hull and Teresa F. Fernandes (In Production) Marine Spatial Planning in Scotland: can climate change scenarios be accommodated?

Kate. S.G. Gormley, Lauren McWhinnie, Joanne. S. Porter, Angela. D. Hull, Teresa. F. Fernandes and William. G. Sanderson (2014) Can Management Effort be predicted for Marine Protected Areas? New considerations for network design. (Marine Policy: accepted – February 2014)

Poster Presentations

- 14th International Conference on Shellfish Restoration: "Shellfish: Our Undervalued Resource", 23rd - 27th August 2011, Stirling, Scotland, UK
- MASTs Annual Science Meeting, September 2011, Edinburgh Conference Centre, Heriot-Watt University, Edinburgh, UK.
- 2012 meeting of the Ecological Genetics Group, 10th - 12th April 2012, Edinburgh Conference Centre, Heriot-Watt University, Edinburgh, UK
- EIMR International Conference, 1st – 3rd May, 2012, Kirkwall, Orkney
- Postgraduate Conference, 6th June 2012, Heriot Watt University, Edinburgh
- SUSFISH 4SEA Conference, "The Future of the Irish Sea: Strategies for Economic and Environmental Sustainability", 12-13th March 2013, Llandudno Junction, North Wales.

Oral Presentations

- MASTs Annual Science Meeting, 11th – 13th September 2012, Edinburgh Conference Centre, Heriot-Watt University, Edinburgh, UK. “Managing Loss: Can we predict the future?”
- SUSFISH Meeting, 15th October 2012, Swansea University, Wales. “Managing Loss: Can we predict the future?” and overview of project.
- *Modiolus modiolus* researchers meeting, Heriot Watt University, Edinburgh. Overview of project.
- SUSFISH 4SEA Conference, "The Future of the Irish Sea: Strategies for Economic and Environmental Sustainability", 12-13th March 2013, Llandudno Junction, North Wales. Presentation delivered by Dr. Joanne Porter.
- ICES Annual Science Conference, 23rd-27th October 2013, Reykjavik, Iceland. "Habitat Winners and Losers: Predictive Habitat Modelling of OSPAR Priority Marine Habitats"

Chapter 1. Introduction

1.1 Background

Pressures on marine biodiversity are set to increase in the future in the coastal and offshore environment and provisions need to be made to protect these valuable resources; while also ensuring various economic activities from energy and blue biotechnology to fisheries or tourism are able to continue to exploit these resources in a sustainable way, now, and into the future (Queffelec *et al.*, 2009).

The EU Marine Strategy Framework Directive (MSFD) has set a requirement to achieve and maintain 'Good Environmental Status' of "biodiversity" in European waters (DEFRA, 2011d), for a number of species and habitats, including those defined as Priority Marine Habitats[1] (PMHs). The implementation of marine management measures and protection (such as Marine Protected Areas; MPAs) will go some way to satisfy these types of policy frameworks, however, prior to these being implemented, the question needs to be asked: **What do marine planners need to know about ecosystems, such as Priority Marine Habitats in order to manage or protect them properly?** An understanding of the ecology of priority species/habitats, and their functioning is necessary to the implementation of Marine Spatial Planning (MSP) and a requirement to achieve Good Environmental Status (GES) under the MSFD (Borja *et al.*, 2011).

Habitat forming species which are encompassed within PMHs such as coral (*Lophelia pertusa*) or shellfish (*Modiolus modiolus*) are of particular interest due to the extended

[1] Priority Marine Habitats as defined by OSPAR and Priority Marine Features as defined by Scottish Natural Heritage (SNH)

communities they ultimately support (such as commercial fish populations). To address some of the questions raised within this thesis, only one Priority Marine Habitat has been selected for primary focus: the horse mussel beds/reefs formed by the bivalve mollusc *Modiolus modiolus*; although studies and methods applied are applicable to other species.

Together, the EU MSFD and Marine Spatial Planning (MSP) are instruments that will facilitate the marine environment to be managed in such a way as to ensure its sustainable functioning; however, this will only be achieved through appropriate implementation. Marine planning is one of the major functions of Marine Scotland and the Marine Management Organisation (MMO) under the Marine (Scotland) Act 2010 and the Marine and Coastal Access Act 2009 respectively and is an essential tool for delivering an ecosystem approach to management (also referred to Ecosystem Based Management; EBM) of the marine environment (Gilliland and Laffoley, 2008). The planning system will help to ensure that marine resources are developed sustainably, with any future developments taking account of environmental effects, the capacity of marine and coastal areas, and minimising and/or mitigating for adverse effects (Harrald and Davies, 2010).

This correct implementation includes the requirement to have an understanding of the functioning of all elements of the marine environment, both physical and biological; and at all trophic levels, from the lowest (e.g. plankton) to the highest (e.g. marine mammals). Traditional monitoring within the marine environment in the waters around the UK has been limited in scope, mainly in part due to lack of guidance on what, when and how things should be monitored. This is in contrast to for example, the Norwegian petroleum industry, which has carried out systematic monitoring of the offshore marine environment since the nineties (CPA, 2011; OSPAR, 2007).

With the onset of the renewable energy “boom” and the implementation of MSP and the MSFD in Europe, these monitoring requirements will have to be addressed. The issues, however, as it has emerged, have still remained the same. For example, certain groups of fauna tend to get precedent over others, primarily marine mammals, seabirds, benthic fauna, sharks and other conservation interest species; with very limited focus on other equally important taxa, for example, plankton (both zoo- and phyto-), fish, and shellfish, and the habitats that they form; despite, the acknowledged requirement for ecosystems to be understood (Borja *et al.*, 2011).

Marine planners need to know about ecosystems, such as Priority Marine Habitats in order to manage or protect them properly. Therefore, to have an understanding of an ecosystem (in this case *Modiolus modiolus*), a number of key questions need to be asked. :

- What do we already know about the ecosystem and what do we need to know?
- What are the risks associated with anthropogenic activities?
- What is the current distribution? What was the historical distribution?
- What data are already available? (e.g. distribution, genetic, what research has already been conducted)
- Are they sensitive or tolerant species to i.e. disturbance, temperature, salinity
- What is their environmental envelope/niche?
- Are geographic distribution and the envelope likely to change? i.e. are they adaptable?
- Are priority habitats/species connected (population to population)?
- What are implications of connectivity vs. fragmentation?
- What are the associated management issues? (National vs. European, transboundary).
- How are risks and impacts to the ecosystem mitigated? (prevention of loss, habitat restoration)
- How the ecosystem is currently protected? Is current protection adequate?

There is no one single research question encompassing this thesis. Instead, the questions outlined above show areas that need further investigation to provide marine planners with the information they require to make informed decisions. This thesis will go some way to contribute to answering some of the questions raised above, through direct studies and the production of scientific evidence and data or through the application, design and development of potential management tools as outlined in the following sections. Each individual study within this thesis sets out their individual research aims and objectives (Chapters 4 – 7); see Section 1.3.1.

1.2 Discussion and Development of Research Theme

1.2.1 Overview

An initial literature review question was set, simply stating: *"within current and developing European marine policy and legislation, what are the key knowledge and research gaps that have been identified (by the scientists and managers responsible for writing the policy and legislation documents), but are yet to be addressed (with particular emphasis on topics potentially associated with commercial and/or conservation shellfish species)?*

A literature review of European marine policy was undertaken (Section 1.2.2), within which a number of knowledge gaps were identified (see Section 1.2.3). It became clear that there was a general lack of sufficient scientific data being incorporated into marine policy encompassing marine ecosystems as a whole. Data incorporated into policy (if at all) were generally focussed on single species or groups (cetaceans, birds etc.), or limited geographic areas (e.g. seabed surveying) and was generally limited in future scope (e.g. incorporating climate change; see Section 1.2.5).

In this research project some of the research gaps identified within the realm of Marine Protected Area management, conservation management and Marine Spatial Plan interactions, with particular emphasis on the development of sound science and an evidence base to underpin the marine planning process will be addressed. The key research theme and initial questions are addressed in more detail in Section 1.2.6.

1.2.2 Environmental Policy and Legislation

A key component of this research project is to provide a thorough understanding and appreciation of the current environmental policies and legislations relevant to the marine environment and Marine Spatial Planning (MSP), to understand how they work together and ultimately how they will help to achieve the defined targets. Initially, it was necessary to identify the policies that should be reviewed and to collate a summary of each of the policies or legislations. The summary of the reviewed policies (listed in Table 1.1) is provided in Appendix A. A summary of the marine environmental/conservation protection in the UK referred to within this thesis and applicable to the reviewed legislation is provided in Table 1.2.

Table 1.1: List of Relevant Marine Legislation, Policy and Frameworks

Policy/Legislation/Framework	Designation Level
Integrated EU Maritime Policy	European Union
Marine Policy Statement	United Kingdom
Marine Strategy Framework Directive (MSFD)	European Union
UK Marine Science Strategy	United Kingdom
UK Biodiversity Action Plan	United Kingdom
Habitats Directive	European Union
Marine and Coastal Access Act 2009 Marine (Scotland) Act 2010	United Kingdom
Water Framework Directive	European Union
Common Fisheries Policy	European Union
Marine Spatial Planning	Global
Marine Protected Areas	Global
Integrated Coastal Zone Management	Global
OSPAR (The Convention for the Protection of the marine Environment of the North-East Atlantic)	North East Atlantic

Table 1.2: UK Environmental Protection

<table>
<tr><th>Type</th><th>Abbreviation</th><th>Region</th><th>Legislation</th><th>Details</th></tr>
<tr><td>Marine Protected Area</td><td>MPA</td><td>Scotland/UK</td><td>Marine (Scotland) Act 2010</td><td rowspan="2">MPAs will take existing SACs, SPAs and SSSI along with new protected sites to create a network of protected sites that will be designated for species, habitats and geology</td></tr>
<tr><td>Marine Conservation Zones</td><td>MCZ</td><td>England, Wales, Northern Ireland</td><td>Marine and Coastal Access Act 2009</td></tr>
<tr><td colspan="5">Marine Protected Areas encompass:</td></tr>
<tr><td>Special Areas of Conservation</td><td>SAC</td><td>EU/UK</td><td>EC Species and Habitats Directive (92/43/EEC)
Offshore Marine Conservation (Natural Habitats & c.) Regulations 2007 (as amended)
Conservation of Habitats and Species Regulations 2010</td><td>Protected site of important high-quality conservation that will make a significant contribution to conserving the habitat types and species identified in the Directive</td></tr>
<tr><td>Special Protection Areas</td><td>SPA</td><td>EU/UK</td><td>EC Directive on the conservation of wild birds (79/409/EEC),</td><td>Sites classified for rare and vulnerable birds and regularly occurring migratory species</td></tr>
<tr><td>Special Sites of Scientific Interest</td><td>SSSI</td><td>UK</td><td>Nature Conservation (Scotland) Act 2004

Wildlife and Countryside Act 1981, as amended by the Countryside and Rights of Way (CROW) Act 2000 and the Natural Environment and Rural Communities (NERC) Act 2006</td><td>Sites that best represent natural heritage (diversity of plants, animals and habitats, rocks and landforms, or a combinations of such natural features)</td></tr>
</table>

1.2.3 Cohesiveness and Integration of Legislation, Policy and Planning

An integrated approach is needed to encompass all issues linked to marine biodiversity in order to create a coherent management strategy; and lessons can be learnt from the implementation of Integrated Coastal Zone Management (ICZM) to inform the development of an ecosystem-based approach for offshore marine biodiversity resources (Queffelec *et al.*, 2009). However, achieving integration between different spatial scales is challenging due to the sectoral nature of most government administrations. In addition, along the coast and at national frontiers, for example throughout Europe, there is usually a division of responsibility and approach (Cooper, 2011).

The evolution of EU policies reflects the international advancements towards achieving a balance between the conservation and exploitation of coastal and marine resources; and the development of the Integrated Maritime Policy demonstrates the EU's desire for a more comprehensive approach to maintaining the benefits of and managing ecosystem resources and services in the offshore marine environment (Queffelec *et al.*, 2009; Perry *et al.*, 2010), which is essentially the driving force behind these policies and regulations. The general scope of ICZM initiatives in Europe has been limited in spatial coverage, with a tendency to be more landward than seaward looking and therefore a critical challenge in the management of marine biodiversity will be to successfully integrate policy aspects for these two spatial territories (Queffelec *et al.*, 2009).

The marine planning aspect is not intended to replace ICZM, but instead will make a significant contribution to ICZM achievement, as Marine Plans will extend up to the level of mean high water spring tides while local authority boundaries generally extend to mean low water mark; and will physically overlap with terrestrial plans. This overlap ensures that marine and land planning will address the whole of the marine and terrestrial environments respectively, and not be restricted by an artificial boundary at the coast; and also means that, organisations and stakeholders need to work together to ensure effective integration of the plans (DEFRA, 2011c).

Integration of policies and plans can generally be divided into legislative (creation of specific legislation that deals with several different sectors), administrative (development of spatial plans or policies, with objectives that influence actions in several sectors) and structural categories (Cooper, 2011). In the UK there is generally a lack of a suitable structural arrangement for integration, and as a result a variety of stakeholder groups, such as coastal partnerships and forums have been formed as a result of "bottom-up" initiatives (Cooper, 2011). Community-based "bottom-up" approaches to integration identify problems and issues that are specific to a local area, meaning that the problems are real and acknowledged, rather than searched for to fit an imposed strategy or policy (Idrus, 2009).

Within the framework of marine policy and governance development in the UK and the EU, it is expected that marine spatial planning will ultimately provide an integrating mechanism for management of the seas, similar to that provided by the terrestrial planning system. However, within this framework, the coast will still require its own specific mechanism to ensure that it is managed in an integrated way (Cooper, 2011).

Overview of Knowledge Gaps

In the UK Marine Policy Statement (MPS) it has been stated that the marine plans will be based on a sound evidence base, as far as possible, and will be developed from a wide range of sources including existing plans. Where evidence is inconclusive, decision makers will be required to make reasonable efforts to fill these gaps, and this will apply equally to the protection of the natural environment, impacts on society and impacts on economic prosperity (HM Goverment, 2011). The UK Marine Science Co-ordination Committee, under which the UK Marine Monitoring and Assessment Strategy (UKMMAS) sits, will provide a platform for addressing the research necessary to fill gaps in knowledge about how both natural and anthropogenic pressures impact on marine ecosystems and how they function (HM Goverment, 2011). At present, the various policies and various accompanying documents are at the stage of identifying where these areas of further work may be, and include, but are not limited to:

1. **National Marine Plan** (Scottish Government, 2011)**:** further work is required to determine the potential impacts of renewable energy, such as general effects on shipping, fishing and biodiversity.
2. **Charting Progress 2** (DEFRA, 2011a)**:** Need to know more about the links between human activities and the marine environment, particularly the cumulative impact of several activities in one area and the ability of a species or habitat to recover once a pressure has been removed.
3. **Charting Progress 2** (DEFRA, 2011a)**:** Need better models that integrate more fully the biological and physical components with pressures at different scales.
4. **Charting Progress 2** (DEFRA, 2011a)**:** Current habitat maps cover only 10% of the UK continental shelf and we are forced to rely on modelling for the rest. For future assessments we will need to improve the accuracy, resolution and scope of these habitat maps by undertaking more surveys and making the existing data more widely available.
5. **Marine Science Strategy** (Scottish Government, 2010)**:** Need to develop scientifically-based methods for assessing the cumulative effects of multiple activities and increasing population pressure on the ecosystem and then translate this into management actions.

6. **Marine Policy Statement** (HM Government, 2011)**:** Identify how the potential impacts of activities will be managed, including cumulative effects.
7. **Marine Policy Statement** (HM Government, 2011)**:** The potential benefits of the introduction of artificial reef structures, which can yield biodiversity benefits and fishing opportunities, have not been fully explored. These should be considered further in the context of marine planning, and for individual developments.
8. **Marine Policy Statement** (HM Government, 2011)**:** To underpin the marine planning process, further research is needed to develop a better understanding of the potential impacts that marine technologies might have on potentially sensitive environmental features.
9. There are many gaps in knowledge about cumulative impacts, general impact assessment methodology and limitations in the current analysis. Further research should seek to help improve understanding of interactions between various stressors and help inform management thresholds and limits for impacts from individual activities and cumulative impacts from multiple activities in a given area (Ban *et al.*, 2010).

Ecosystem-Based Management

For the last three decades, EU environmental policies have focused on determining adverse and undesirable changes to the natural system as the result of human activities and then, if any adverse change is detected, initiate management responses to alleviate those adverse changes (Borja *et al.*, 2010); in addition to management of resources, environmental assessment and monitoring primarily focuses on single industry sectors in many regions (Kenny *et al.*, 2009; Queffelec *et al.*, 2009). There has now been a shift in the perception of environmental management as it has moved up the political agenda, with a move towards both an integrated and ecosystem-based management system (EBM); a requirement for quantitative cumulative impact assessment and mapping; and integrated monitoring measures. EBM represents a departure from single species or single sector management, focussing on the full range of benefits provided by the coasts and oceans (i.e., ecosystem services) and the inherent trade-offs in our management of the many activities that affect these systems (Lester *et al.*, 2010). Many of the principles of EBM are not considered to be new; but rather build upon the pre-existing approaches to natural resource management such as integrated coastal zone management (Lester *et al.*, 2010).

The core goal of EBM is to maintain healthy ecosystems capable of providing a range of benefits (Lester *et al.*, 2010; McLeod *et al.*, 2005). Collectively referred to as ecosystem services, these benefits, including food, energy, recreational opportunities, and shoreline protection, are declining or are seriously compromised in coastal and ocean ecosystems around the world (Lester *et al.*, 2010; Foley *et al.*, 2010; UNEP, 2006).

The principle of EBM is a common and continued theme running through all the policies described in Appendix A; and it is an essential component of each of the policies which will complement each other; but not necessarily be fully integrated with one another. For example, the NMP documents will ultimately be complemented by the Programme of Measures to fulfil the delivery of GES under the MSFD (between 2012 and 2015). It has been acknowledged that the integration of the Programme of Measures into the NMP will be essential to achieve GES by 2020 (Scottish Government, 2011).

However, the key issue that may arise from this is whether the objective or outcome of one particular policy, ultimately impact upon the objectives of another. It is stated within the Marine Science Strategy (MSS) that (DEFRA, 2010):

> *"One of the policy needs that has been identified is to know how well the ecological impact of different policy options can be predicted, including the effects of any management actions taken on the ecosystem."*

This statement can be considered true for each of the individual policies, but also when considering all policies together in practice – and how the eventual policy designations and decisions (particularly the decisions arising from the National and Regional Marine Spatial Plans; regional at a UK level in this context) may ultimately and cumulatively impact upon the marine ecosystem and services.

The Marine Policy Statement (HM Government, 2011) states that:

> "*There is a wide range of legislative provisions (and other biodiversity and ecologically relevant obligations) at international and national level that Marine Plans need to take into account. These include the MSFD (Directive*

2008/56/EC), Water Framework Directive (WFD) (Directive 2000/60/E) C, Habitats Directive and Wild Birds Directive."

An example of where this may be of issue has been described in the NMP pre-consultation draft with regard to the effects of MSP on food webs. In summary, the issue may arise that a creation of a no-take fishing zone, or an MPA may lead to increased predation of some species, or similarly areas designated as renewable zones may create areas of decreased predation, which, might impact positively or negatively on the food web dynamics of the area; and would ultimately impact on the measures required to meet the GES requirements on the MSFD. In addition, a reduction of plankton eating fish stocks is also likely to result in a larger proportion of the plankton production falling out to the seabed, which enhances growth of benthic species, and in turn would be reflected in higher catches of for example prawns (*Nephrops*) or crabs (Scottish Government, 2011).

1.2.4 Climate Change and Policy

The effect that climate change has on the geographic distribution of species is often assessed in terms of potential envelopes/spatial niches shifting in altitude, longitude or latitude; and this influence could potentially threaten biodiversity and conservation of the species (del Barrio *et al.*, 2006). Generally, the impacts of climate change are still perceived to be distant and are generally ignored in developing day-to-day ocean management strategies (Ruckelshaus *et al.*, 2013). In fact a literature review on the potential integration or acknowledgement of climate change within a marine environmental policy/legislation context showed that research or thought is lacking in this area. From a terrestrial point of view, biodiversity conservation mainly relies on fixed protected areas, with a requirement to protect specific species assemblages and ecosystems, and with expected climate change, many species and vegetation types are expected to lose representation in protected areas over time (Heller and Zavaleta, 2009). This is also true within the marine environment, and was one point that contributed to the research project development.

The key questions outlined in the Section 1.1 (described in more detail in Section 1.2.5) set the scene for the possibility that an ecosystem may change over time and research gaps may arise as a result. Understanding whether an ecosystem will change, in composition or distribution, as a result of a changing climate is a particularly pertinent management question at present. Will the ecosystem be lost? Will the ecosystem move? Can current protection adapt? How will nations manage transboundary issues?

Obviously, answering speculative future questions such as those outlined above is problematic. The use of Species Distribution Models (SDMs) for example can contribute to marine planning and conservation as they can predict spatial changes to distribution as a species responds to climate change. These models may ultimately provide a robust and cost efficient management tool, providing due consideration is given to their limitations and uncertainties.

1.3 Thesis Aim and Objectives

In order to develop the necessary plans for integrated management, as part of an “ecosystem approach to management”, it is essential to have an adequate understanding of the ecosystem in which management is occurring ("Knowledge of Ecosystem"). This would need to include identifying the features of the ecosystem (see Section 1.1), which are considered to be structurally and functionally important, the nature and intensity of the human activities and how the ecosystem features (including human activities) interact on different time and spatial scales (Kenny *et al.*, 2009; Scott, 2009).

The flow diagram in Figure 1.1 outlines the research questions set, its intended direction and application, including a description of the literature review methodology and thought process involved in setting out the individual study research questions.

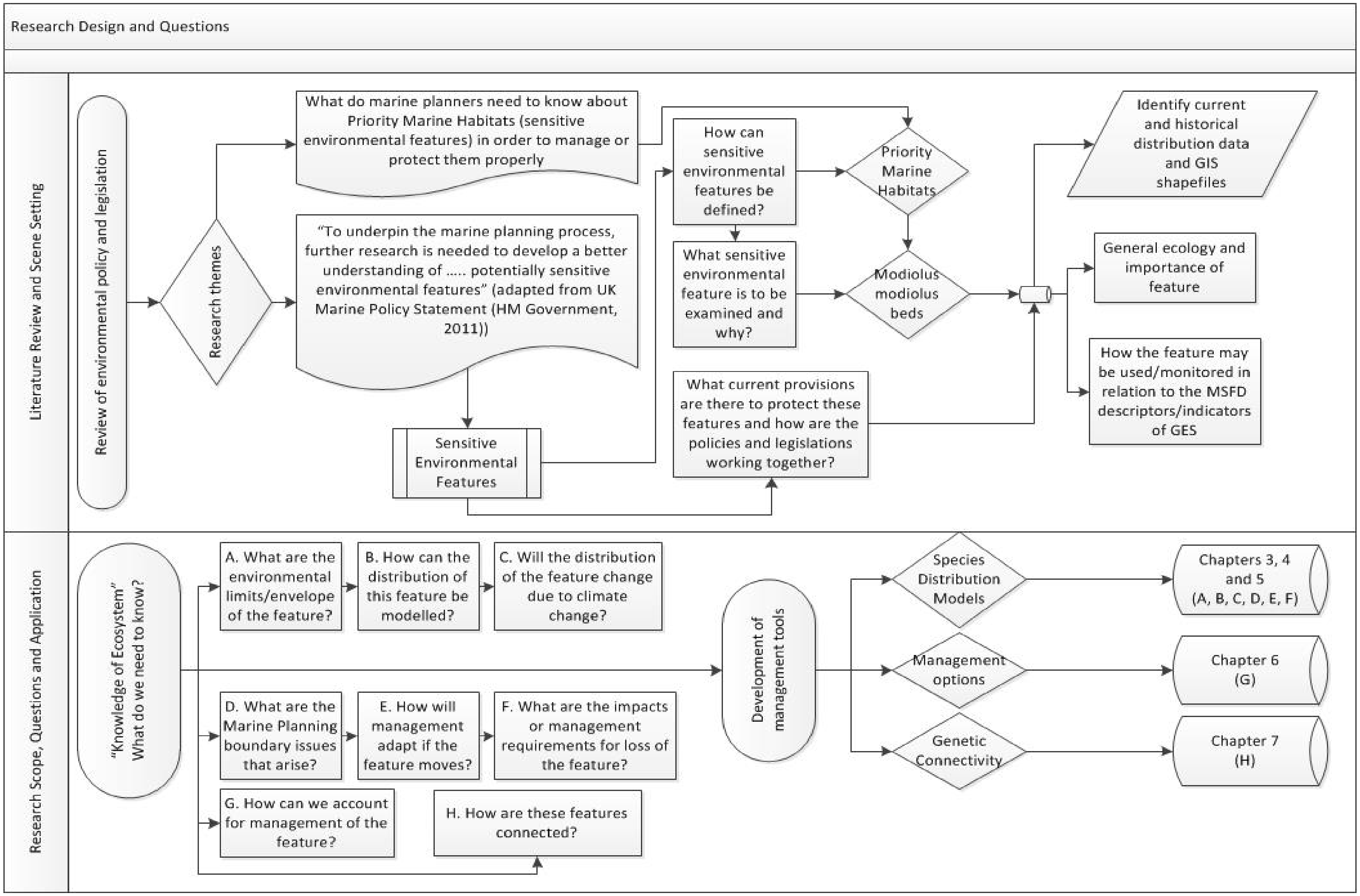

Figure 1.1: Flow Diagram of Research Design and Research Questions

1.3.1 Project Layout and process

In the chapters of this thesis, the principles of "science to underpin the marine planning process" are investigated. Techniques, both established and novel, are used to generate evidence to support policy making strategies, and tools that can be used and developed to aid the decision making process. Chapters 1 and 2 provide background information to the research question and the study species. Chapter 3 introduces the methods and data mining carried out in preparation for the following chapters. Chapters 4, 5, 6 and 7 are separate studies in their own right. Separate introduction, methods, results and discussion sections describe the investigative studies carried out. These chapters describe, develop and discuss the tools that have been selected as best assessors of a Priority Marine Habitat ecosystem. In Chapter 8 a discussion is provided of the overall thesis and how these studies are related, how they can influence policy, and ultimately how the research can be used by the decision makers. The chapters aim to address the identified questions as follows:

- How do we define a sensitive environmental feature? A literature review was carried out to gain an understanding of the ecology, distribution and factors influencing the chosen Priority Marine Habitat, *Modiolus modiolus* beds (**Chapter 2**)
- To understand how *Modiolus modiolus* may respond to a scenario where ocean temperatures increase, what are the best methods for doing this? To make our research usable to policy managers, we need to ensure that the methods investigated are easily accessible, relatively straight-forward to learn or implement, provide robust enough results and where possible be freely available. Data availability is a significant factor to be considered. Method selection is dependent on the type of data that is required. A range of potential methods were investigated and trialled. Data on species distribution and environmental variables will be gathered from available sources and selection of study methods will then be made. **Chapter 3** will introduce the concept of Species Distribution Modelling, data availability and collection.
- Following method selection, method testing will be required over a suitable geographic region, data and environmental variables will be prepared. This study investigates the hypothesis that the distribution and extent of Priority Marine Habitats may change as a result of climate change, and results will be

analysed to determine to what extent loss may occur and what implications this may have on marine environmental management, particularly from a MSFD and MPA perspective (**Chapter 4**)

- Following on from the study in Chapter 4, the concept of loss and/or movement of Priority Marine Habitats will be considered within a wider geographic setting. Is the loss of the species from our original geographic location correct? Or is there simply a movement to other areas? And will the same movements occur for other species? The selected SDM method will be applied to more Priority Marine Habitats species over a wider study area (Europe). The study will again provide evidence that potential movements, loss or gains of species may occur over time and under an increased ocean temperature scenario. The study will examine how policy managers between regions will have to incorporate these issues between neighbouring regions (see Section 1.2.4) now and into the future (**Chapter 5**)
- While considering marine environmental policy and conservation in the previous chapters and through the attendance of meetings and public consultations, it became evident that the management of MPAs was of particular interest from a research perspective. Policy managers had ideas on what management strategies would be employed, but not what these management options may actually mean in terms of effort and cost for the future. This study is developed using data produced and utilised in Chapter 4 to create an MPA predictive management indicator. The tool will provide a means to identify which of the proposed MPAs may be more time-consuming from a management perspective. It will also provide the first steps to help towards a cumulative impact assessment of human activities on MPAs, and provide some initial perspective to the knowledge gaps identified in Section 1.2.3 (**Chapter 6**)
- Following on from the modelling methods in Chapters 4 and 5, and the MPA management in Chapter 6, ground truthing will be required to validate the models. It was decided that in order to understand the potential future movement of *Modiolus modiolus* beds, understanding their present connectivity will be required. Microsatellite primers will be developed and screened for *M. modiolus* populations. The results will determine whether habitats are

connected, and whether any potential movement identified within the models, would actually be possible given the direction of the gene flow (**Chapter 7**)

- Chapter 8 will provide an overall discussion and an overview of the interconnection of the individual studies described above, what key aspects were discovered and identifies potential future research avenues (**Chapter 8**).

Chapter 2. Priority Marine Habitats

2.1 Study Subject Background

This thesis investigates a ‘sensitive environmental feature’ and applies a variety of methods, including: Species Distribution Modelling (SDM) and genetic connectivity. Using the academic literature and governmental reports, in this chapter an explanation is provided on how sensitive environmental features are defined in the context of UK marine conservation interest and why they are considered to be important within the marine environment. It was therefore necessary to select a test subject that would be robust enough to be used within an identified model (including data availability); would be reasonably easy to sample; and applicable to marine conservation and planning.

Research of both academic and grey literature has shown that there is no definitive definition for the term "sensitive environmental feature" and it is generally applied to any environment which may be susceptible to a particular impact; and in that context therefore, it could be defined as any receiving environment (e.g. river, woodland, coast, ocean etc.) depending on the activities implied. For example, water bodies (as a general term; streams, estuaries etc.) may be considered as sensitive environmental features when considering agricultural land runoff (Lewis and Bardon, 1998); or forestry activities effecting wetlands (Bonnell, 2003); and in fact, in a number of studies, the term "sensitive environmental feature" is used as a blanket term and is poorly defined, if at all (Rose and Suffling, 2001; Beuschel and Rudel, 2009; Geißler *et al.*, 2013).

For the basis of this study a ‘sensitive environmental feature’ has been interpreted as a Priority Marine Feature (PMF) as described by Scottish Natural Heritage (SNH), the

Joint Nature Conservation Committee (JNCC) and under the OSPAR Convention[2] as a Priority Marine Habitat (determined as 'threatened and/or declining species and habitats'). This study will refer to them as Priority Marine Habitats (PMHs) in a European context or as Priority Marine Features (PMFs) in a UK or Scotland only context.

PMFs are species and habitats that have been identified through a scientific evaluation of Scotland's marine biodiversity; and represent species and habitats of greatest marine conservation importance in Scottish territorial waters, (Marine Scotland, 2011; SNH, 2011b). SNH has created a draft PMF list containing 53 habitats and species that will be used to guide future research and support the advice SNH provides on marine biodiversity (full list in Appendix B;) (SNH, 2011b).

Priority Marine Habitats (determined as 'threatened and/or declining species and habitats' under the OSPAR Convention for the Protection of the Marine Environment of the north-east Atlantic 1992) are considered to be of greatest marine nature conservation importance within the North-East Atlantic and are being used to prioritise marine biodiversity conservation and protection under Annex V of the OSPAR Convention 1992. The maintenance of priority habitats will also contribute to the achievement of 'Good Environmental Status' (GES) under the European Union (EU) Marine Strategy Framework Directive (MSFD; 2008/56/EC; see also Moffat *et al*. (2011)). Appropriate area-based management strategies, including a network of Marine Protected Areas (MPAs) are being considered under the MSFD with these and other habitats in mind (SNH, 2011b).

Guidance outlining existing legislative protection and management requirements of each of the identified PMFs is currently being prepared by SNH (as of May 2011). The guidance will ultimately include an assessment of known feature 'sensitivities' and maps of Scottish distribution. It is aimed to create a list of features that will be subdivided to outline the most appropriate management option, such as (Marine Scotland, 2011; SNH, 2011b):

- New area-based mechanisms, such as through the creation of Marine Protected Areas and the emerging marine planning system;

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[2] The Convention for the Protection of the Marine Environment of the North-East Atlantic (the Oslo-Paris (OSPAR) Convention)

- Non-area based mechanisms to achieve better protection, than is currently afforded them, and for which action will be prioritised via a three-pillar approach, (i.e. species measures, site-based measures, and wider seas policies and measures as set out in Marine Scotland's Marine Nature Conservation Strategy);
- Features of importance to the wider functioning of the marine ecosystem; and
- In addition, a subset of 6-10 habitats or species for which it is possible to make a significant difference as part of the Scottish Marine Biodiversity Implementation Plan will also be identified.

The list of PMF habitats, species and large-scale features of functional importance to Scotland's seas (collectively termed Marine Protected Area (MPA) search features) will drive the identification of Nature Conservation MPAs (Moore and James, 2011). The MPA network in Scottish waters will comprise existing protected areas, primarily European marine sites (SACs under the Habitats Directive and Special Protection Areas (SPAs) under the Birds Directive), as well as those subject to other types of area-based management, and MPAs designated under the Marine (Scotland) Act 2010 and the UK Marine and Coastal Access Act 2009 (Moore and James, 2011).

For the basis of this study, the focus was restricted to habitat forming species. An overview of these PMHs is outlined in Table 2.1 and mapped in Figures 2.1 to 2.11.

Table 2.1: Priority Marine Habitats present in North-East Atlantic (OSPAR Region)

Priority Marine Feature	**Definition**
Lophelia pertusa (Linnaeus, 1758) reefs	Reefs of the coral *Lophelia pertusa* extending over at least $25m^2$. (Figure 2.1)
Coral Gardens	A relatively dense aggregation extending over at least $25m^2$ of colonies or individuals of one or more coral species, such as leather corals (*Alcyonacea*), gorgonians (*Gorgonacea*), sea pens (*Pennatulacea*), black corals (*Antipatharia*), hard corals (*Scleractinia*) and, in some places, stony hydroids (lace or hydrocorals: *Stylasteridae*). (Figure 2.2)
Sea-pen and burrowing megafauna communities	Plains of fine mud, extending over an area of at least $25m^2$ and at water depths ranging from 15-200m or more, which are heavily bioturbated by burrowing megafauna, with burrows and mounds typically forming a prominent feature of the sediment surface, and which may include conspicuous populations of sea-pens, typically *Virgularia mirabilis* (Müller, 1776) and *Pennatula phosphorea* Linnaeus, 1758. (Figure 2.3)
Deep-sea sponge aggregations	Aggregations of deep-sea sponges extending over at least $25m^2$ that are principally composed of sponges from two classes: *Hexactinellida* and *Demospongia*. (Figure 2.4)
Littoral Chalk Communities	Formation of vertical cliffs and gently sloping intertidal platforms supporting a range of micro-habitats of biological importance, including the alga assemblages of Haptophyceae species. Lower on the shore 'rock-boring' invertebrates such as piddocks and *Polydora* sp. overlain by algal dominated communities are present. (Figure 2.5)
Modiolus modiolus (Linnaeus, 1758) Horse Mussel Beds	Dense beds of *Modiolus modiolus* at depths up to 70m on a range of substratum. Communities associated with these beds are diverse. Patches extending over $>10m^2$ with >30% cover by mussels should be classed as a "bed". (Figure 2.6)
Zostera Beds	Beds of the seagrass *Zostera marina* Linnaeus, 1753 or *Zostera noltii* Hornemann, 1832. Plant densities should provide at least 5% cover, but >30% cover is more typically sought. (Figure 2.7)

Table 2.1 (continued): Priority Marine Habitats present in North-East Atlantic (OSPAR Region)

Priority Marine Feature	Definition
Maerl Beds	A collective term for various species of non-jointed coralline red algae (Corallinaceae). Extensive beds can be formed, mostly in coarse clean sediments of gravels and clean sands or muddy mixed sediments either on the open coast, in tide-swept channels or in sheltered areas of marine inlets with weak current. (Figure 2.8)
Sabellaria spinulosa Leuckart, 1849 reefs	The tube-dwelling polychaete *Sabellaria spinulosa* can form dense aggregations on mixed substrata and on rocky habitats. The *Sabellaria* covers 30% or more of the substrata and is sufficiently thick and persistent to support an associated epibiota community, distinct from surrounding habitats. (Figure 2.9)
Intertidal *Mytilus edulis* Linnaeus, 1758 beds on mixed and sandy sediments	Sediment shores characterised by beds of mussel *Mytilus edulis* occur on mid and lower shore mixed substrata. In high densities (>30% cover) the mussels bind the sediment and provide a habitat for infaunal and epifaunal species. (Figure 2.10)
Ostrea edulis Linnaeus, 1758 beds	occurring at densities of 5 or more per m^2 on shallow mostly sheltered sediments (typically 0-10m depth, but occasionally down to 30m) (Figure 2.11)

Source: (OSPAR Commission, 2004)

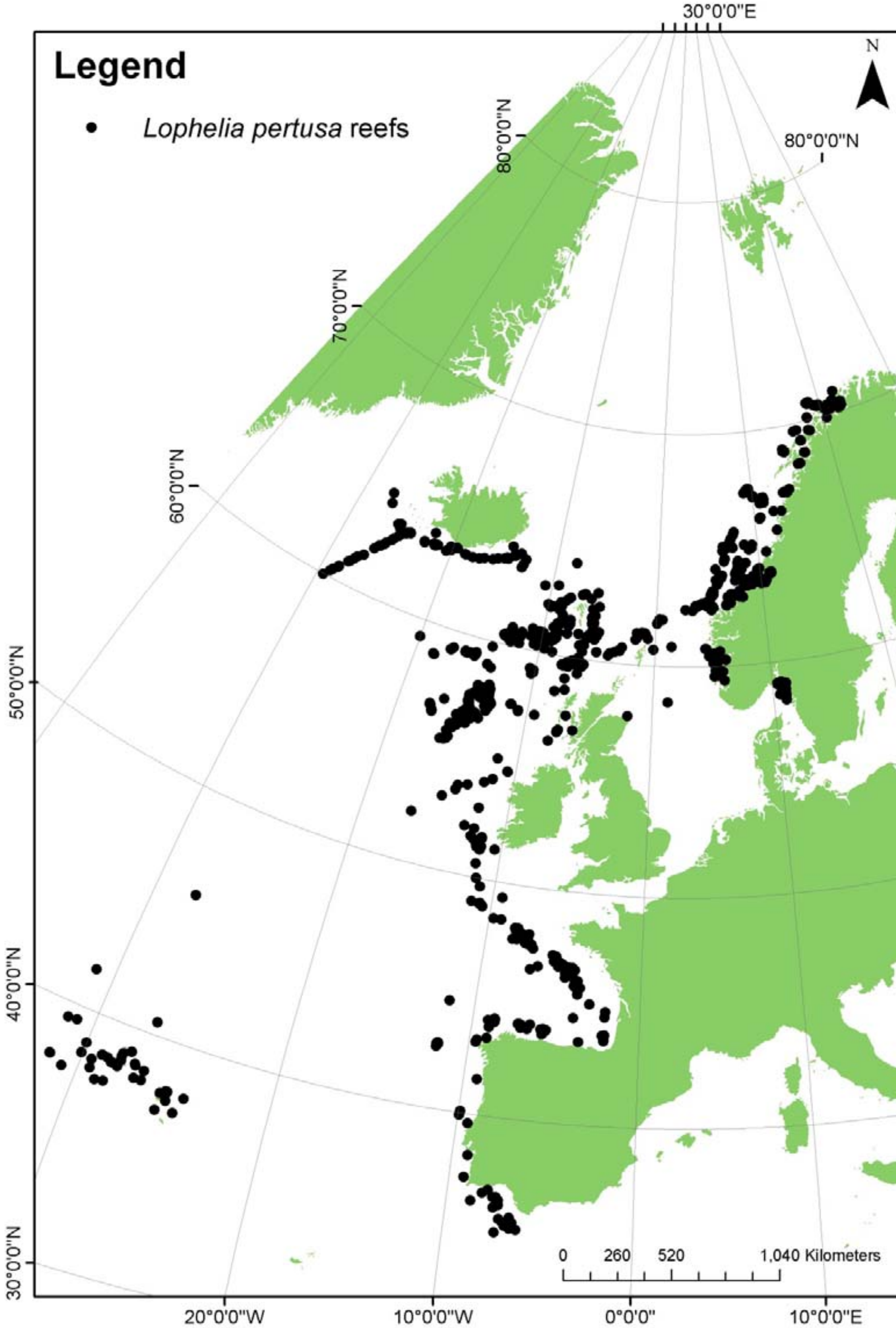


Figure 2.1: Distribution of the Priority Marine Habitat, *Lophelia pertusa* reefs, in the North-East Atlantic

Data Source: 2012 OSPAR Priority Marine Habitats dataset, OSPAR Commission/JNCC (JNCC, 2012a)

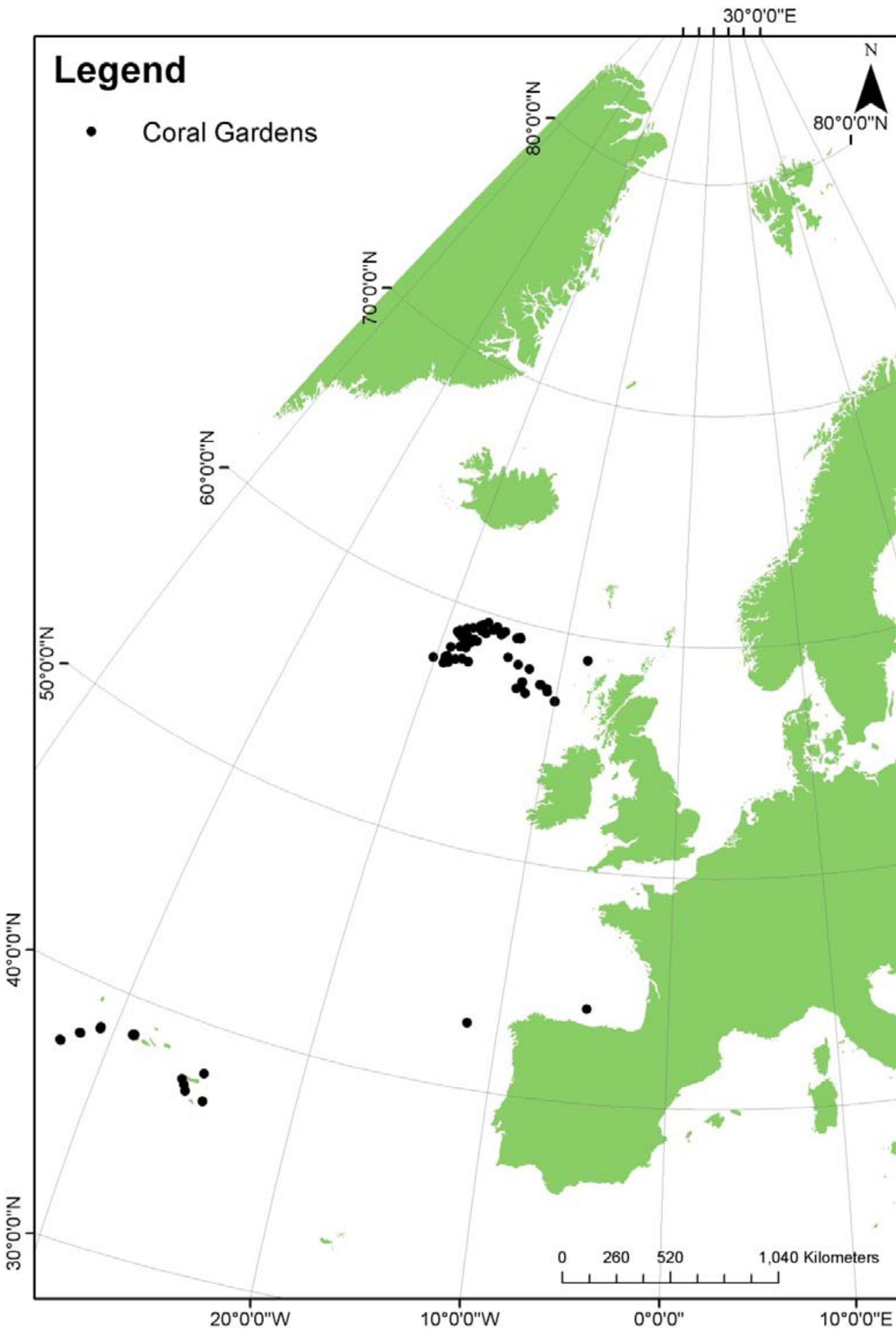


Figure 2.2: Distribution of the Priority Marine Habitat, Coral Gardens, in the North-East Atlantic

Data Source: 2012 OSPAR Priority Marine Habitats dataset, OSPAR Commission/JNCC (JNCC, 2012a)

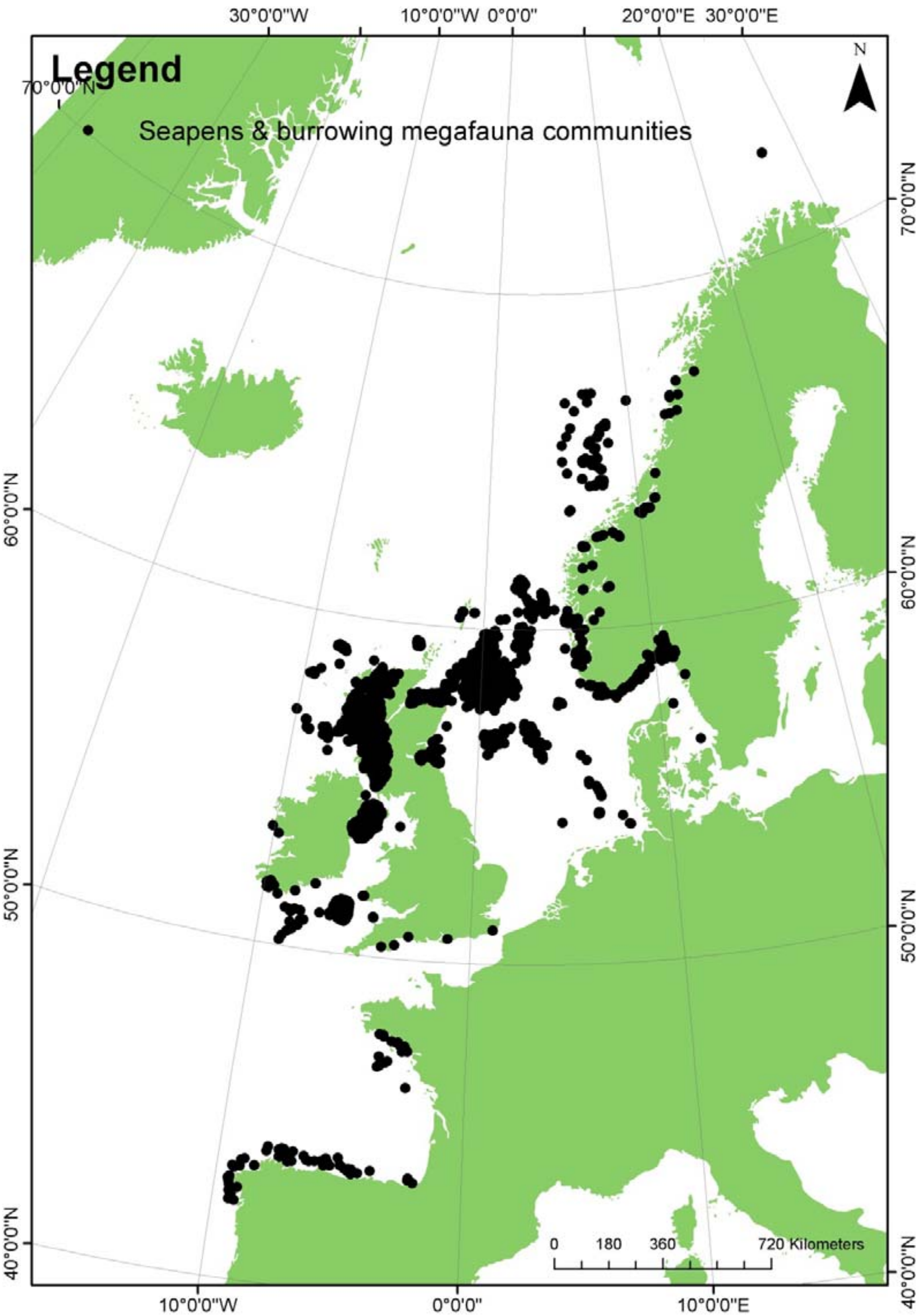


Figure 2.3: Distribution of the Priority Marine Habitat, Seapens and Burrowing Megafauna Communities, in the North-East Atlantic

Data Source: 2012 OSPAR Priority Marine Habitats dataset, OSPAR Commission/JNCC (JNCC, 2012a)

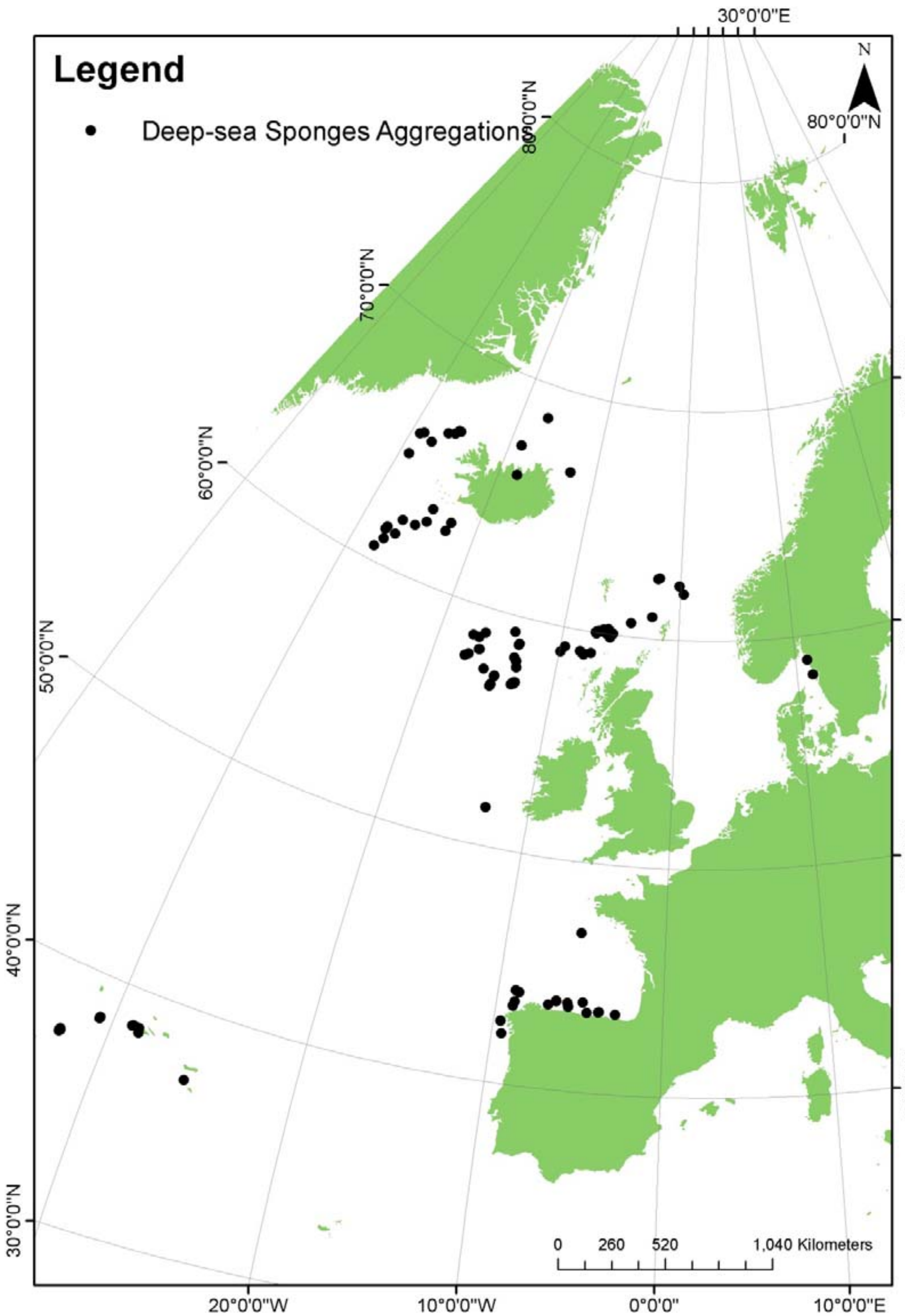


Figure 2.4: Distribution of the Priority Marine Habitat, Deep-sea Sponge Aggregations, in the North-East Atlantic

Data Source: 2012 OSPAR Priority Marine Habitats dataset, OSPAR Commission/JNCC (JNCC, 2012a)

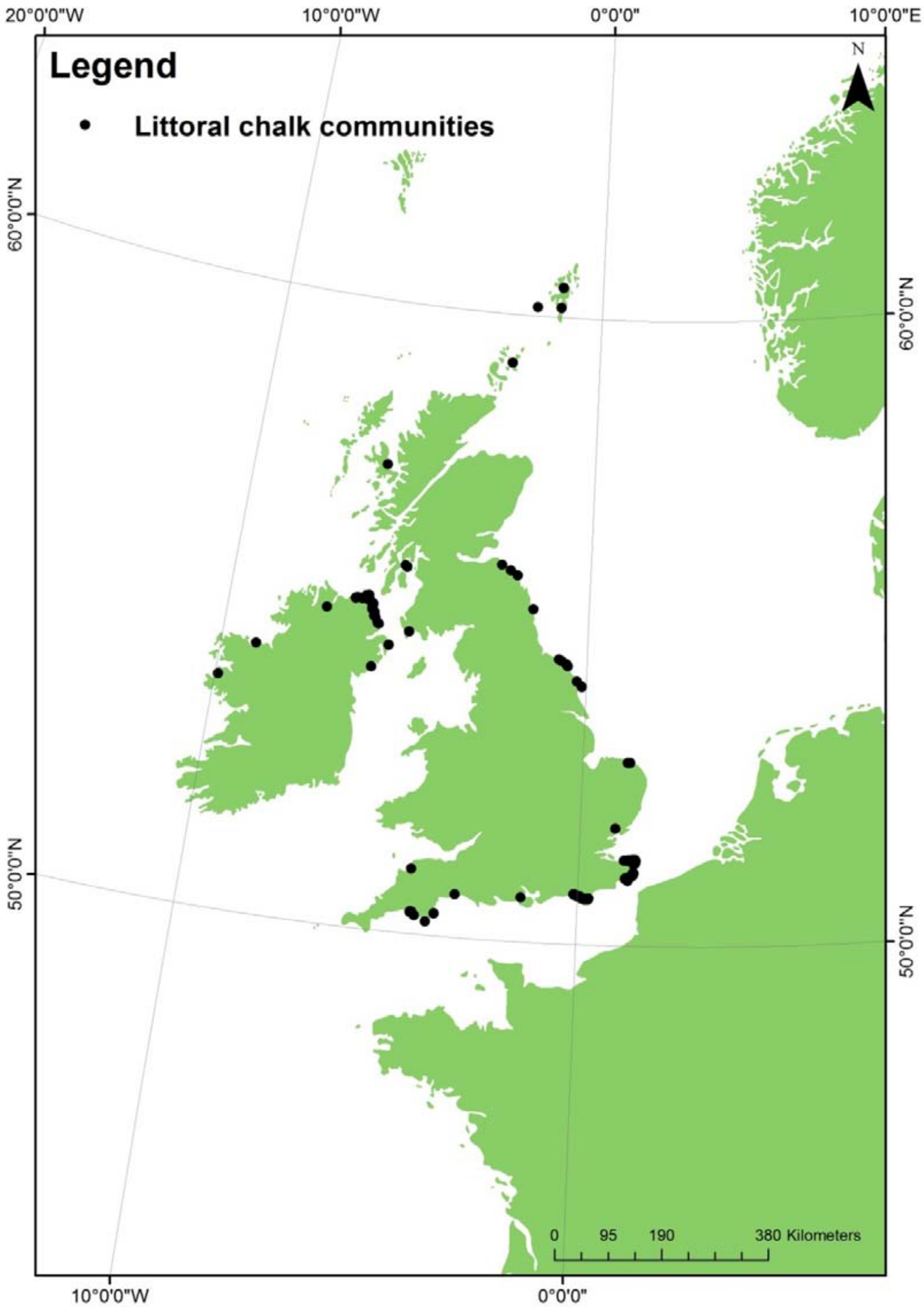


Figure 2.5: Distribution of the Priority Marine Habitat, Littoral Chalk Commnuities, in the North-East Atlantic

Data Source: 2012 OSPAR Priority Marine Habitats dataset, OSPAR Commission/JNCC (JNCC, 2012a)

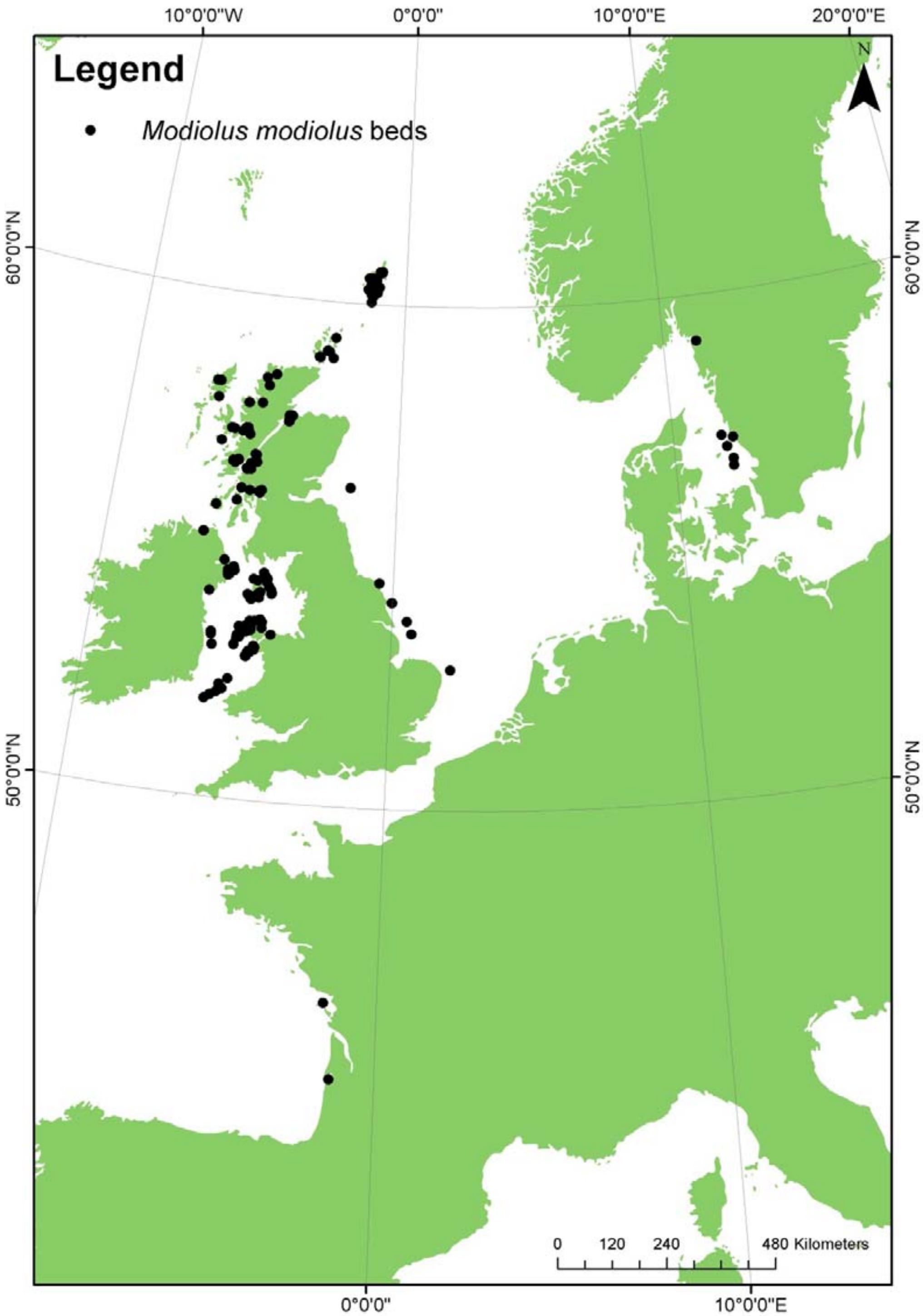


Figure 2.6: Distribution of the Priority Marine Habitat, *Modiolus modiolus* beds, in the North-East Atlantic

Data Source: 2012 OSPAR Priority Marine Habitats dataset, OSPAR Commission/JNCC (JNCC, 2012a)

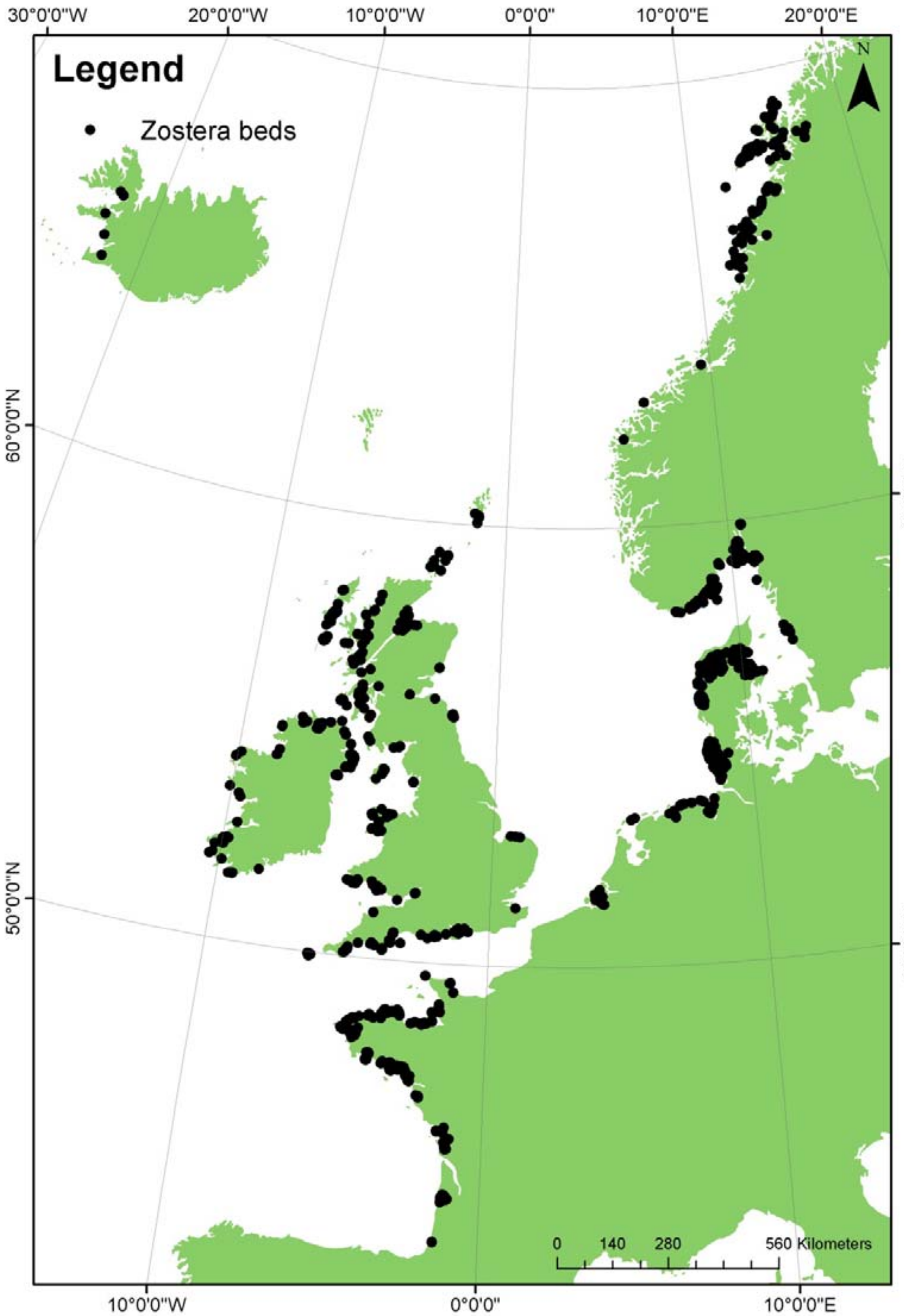


Figure 2.7: Distribution of the Priority Marine Habitat, Zostera beds, in the North-East Atlantic

Data Source: 2012 OSPAR Priority Marine Habitats dataset, OSPAR Commission/JNCC (JNCC, 2012a)

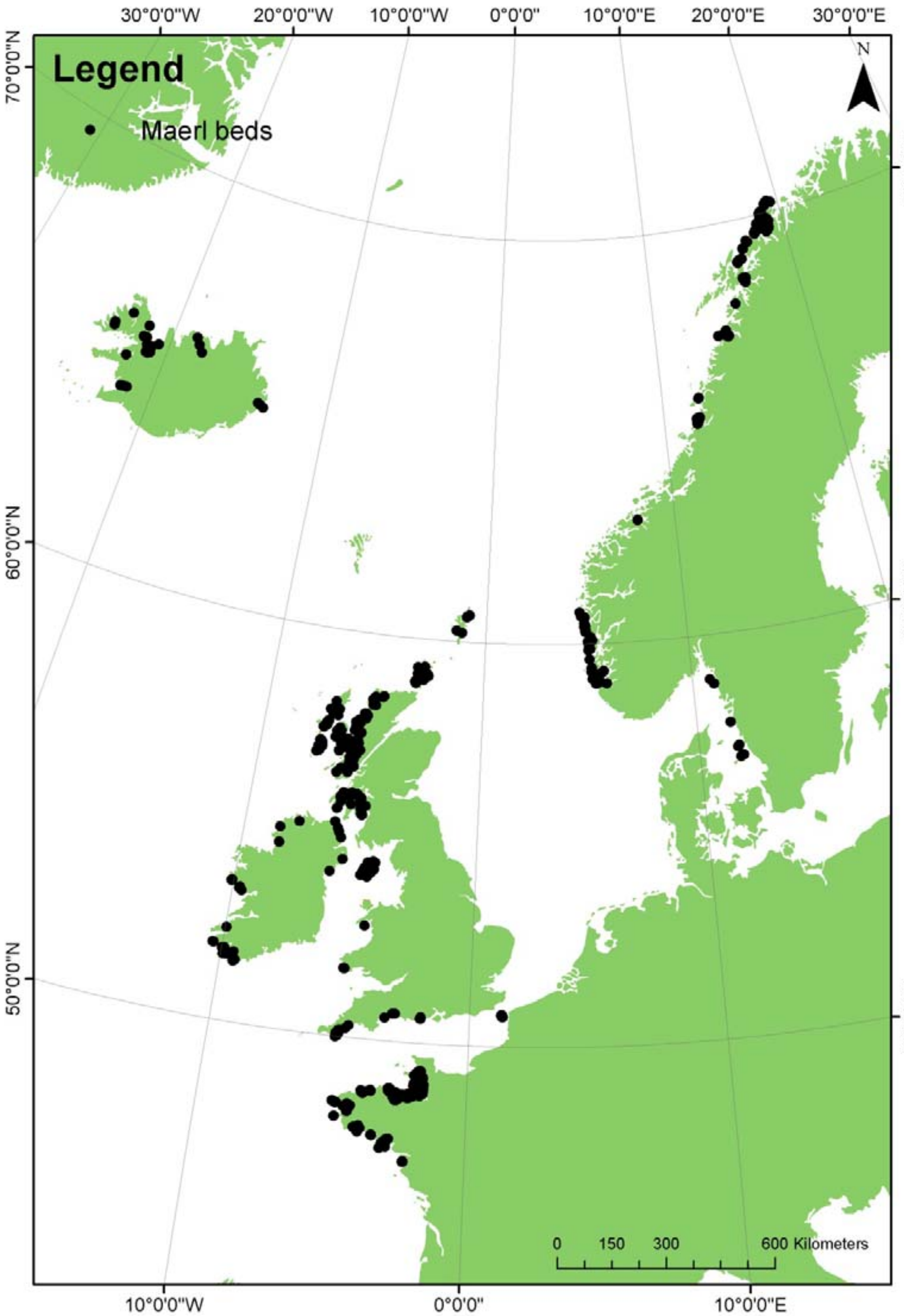


Figure 2.8: Distribution of the Priority Marine Habitat, Maerl beds, in the North-East Atlantic

Data Source: 2012 OSPAR Priority Marine Habitats dataset, OSPAR Commission/JNCC (JNCC, 2012a)

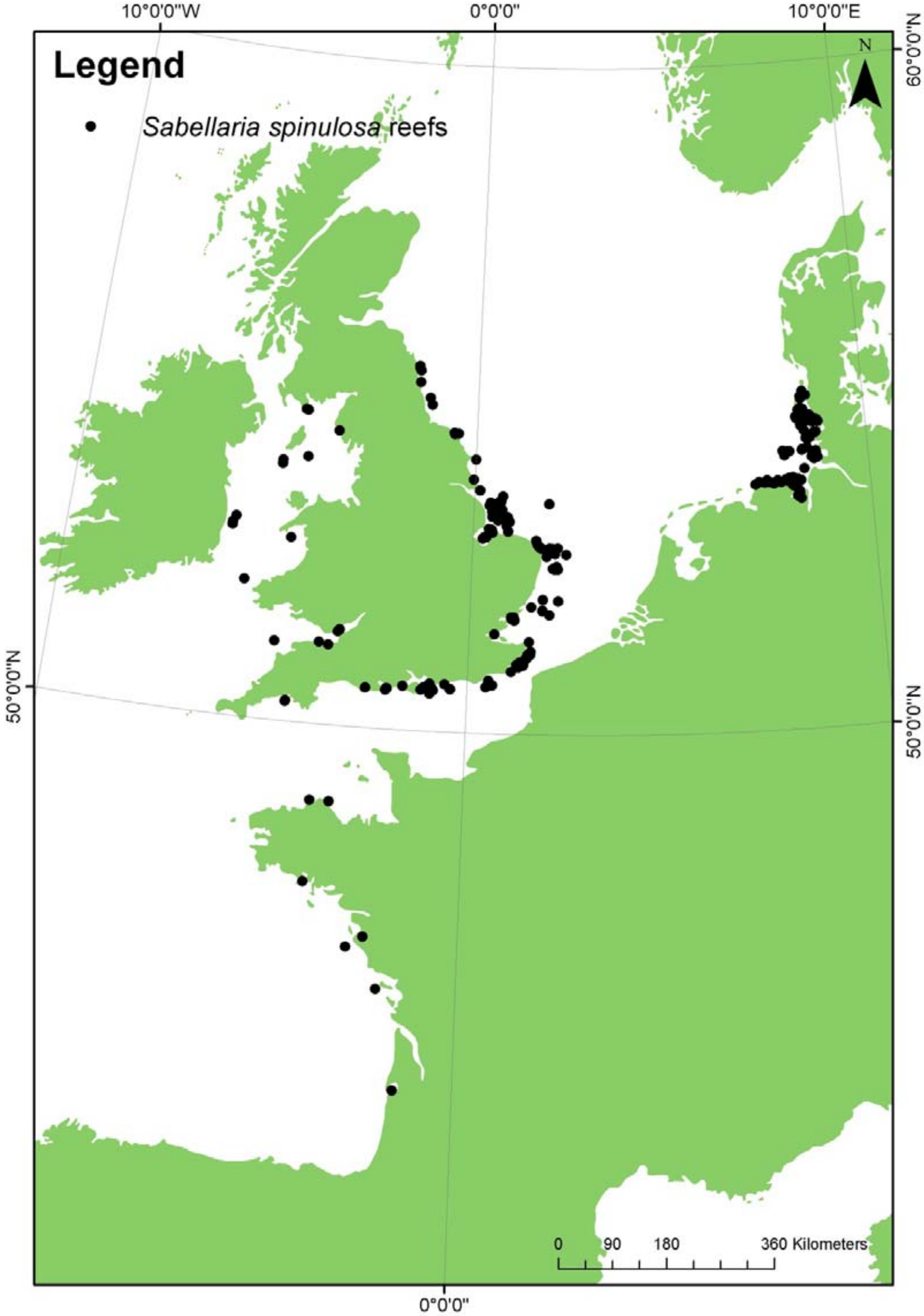


Figure 2.9: Distribution of the Priority Marine Habitat, *Sabellaria spinulosa* reefs, in the North-East Atlantic

Data Source: 2012 OSPAR Priority Marine Habitats dataset, OSPAR Commission/JNCC (JNCC, 2012a)

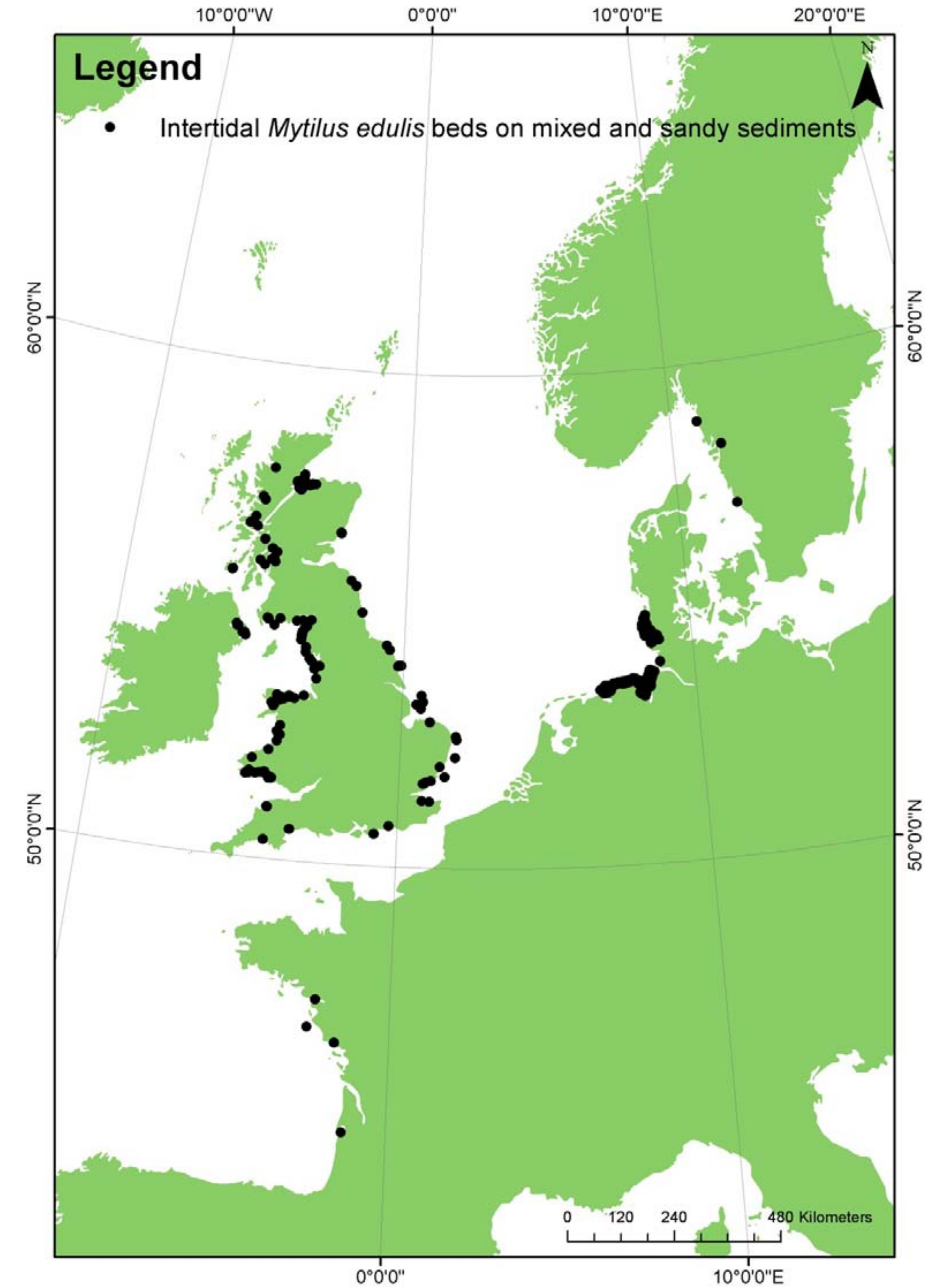


Figure 2.10: Distribution of the Priority Marine Habitat, Intertidal *Mytilus edulis* beds of mixed and sandy sediments, in the North-East Atlantic

Data Source: 2012 OSPAR Priority Marine Habitats dataset, OSPAR Commission/JNCC (JNCC, 2012a)

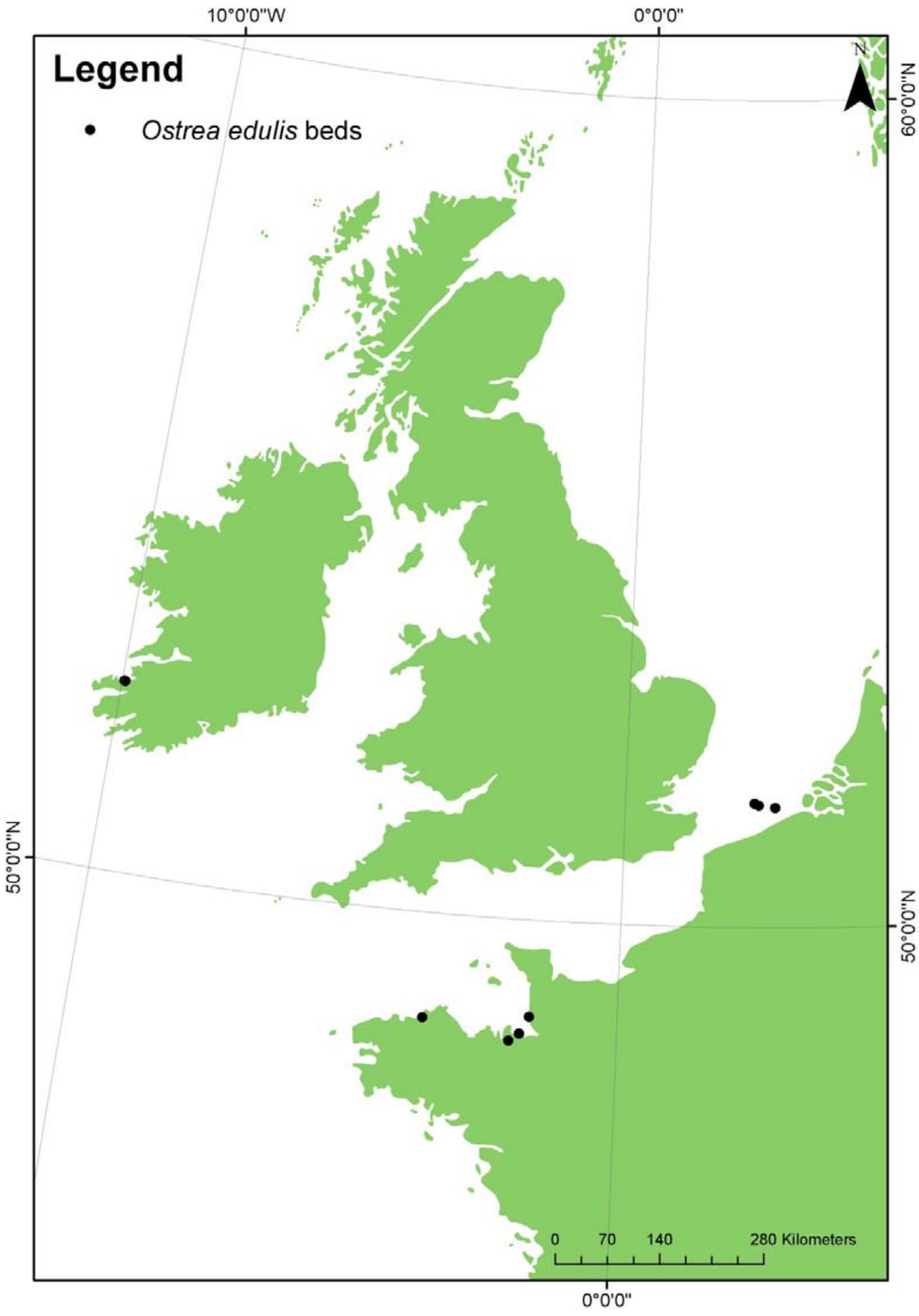


Figure 2.11: Distribution of the Priority Marine Habitat, *Ostrea edulis* beds, in the North-East Atlantic

Data Source: 2012 OSPAR Priority Marine Habitats dataset, OSPAR Commission/JNCC (JNCC, 2012a)

2.2 Priority Marine Habitat used in present study

A number of priority habitats/species were identified as potentially being suitable as a study subject within this project, of which the reef forming bivalve mollusc *Modiolus modiolus* (horse mussel; Figure 2.12) was selected to be the principal case study. All PMHs outlined in Table 2.1 will be considered in Chapter 5.

Figure 2.12: *Modiolus modiolus* bed, Loch Creran

Source: Robert Cook, Heriot Watt University.

This species was identified as being the best study candidate as it is relatively large and easily identifiable; and although beds are subtidal, making diver recovery essential, parallel diving based projects on *M. modiolus* were being undertaken at the time, therefore allowing for collaborative sampling and reduction of potential over sampling and environmental impacts (further suitability factors are discussed in Section 2.7).

In addition to its listing by OSPAR and as a Priority Marine Habitat and as a PMF by SNH/JNCC, *M. modiolus* is subject to several local, national and regional listings;

including the Habitats Directive[3] (as part of a biogenic reef habitat) and the UK Biodiversity Action Plan (UKBAP) (Rees, 2009c).

2.2.1 Biogenic Reefs

Biogenic reefs in UK waters can comprise a number of different organisms including the horse mussel *Modiolus modiolus*, the blue mussel *Mytilus edulis*, the Ross worm *Saballeria spinulosa*, the cold water coral *Lophelia pertusa*, the honeycomb worm *Saballeria alveolata* (Linnaeus, 1767) and the tubeworm *Serpula vermicularis* Linnaeus, 1767.

The definition of a "biogenic reef" is open to interpretation and varies between reports and between reporting organisations. These difficulties arise as there are many cases of continuous gradations between communities which are not considered reefs (e.g. scattered *Modiolus* within a gravel bed etc.) and those which are (e.g. continuous, dense, raised aggregations of *Modiolus* etc.) (UK Marine SAC Projects, 2001a). In addition, definition and classification of *M. modiolus* reefs/beds in particular, is rarely conclusive, due to the fact that the beds often occur as quite small features and are often patchy and intermittent (Rees, 2009c). Difficulty also arises in implementing the Habitats Directive and the various challenges associated with monitoring the status of, for example, *S. spinulosa* reefs, as this requires the organism in question to form a distinct entity, defined in such a way as to distinguish them from other habitats or biotopes (Hendrick and Foster-Smith, 2006). This debate over the distinction of what is classified a 'reef' is problematic from both a regulator and industry point of view; and this ambiguity is particularly problematic in relation to the assessment of potential impacts and effects of proposed developments, such as wind farms, seabed trawling and dredging (Hendrick and Foster-Smith, 2006). Three such definitions of biogenic reefs are described below.

- Brown *et al.* (1997) [Accessed at: http://jncc.defra.gov.uk/ProtectedSites/SACselection/habitat.asp?FeatureIntCode=H1170] define reefs as: *"Reefs are rocky marine habitats or biological concretions that rise from the sea bed. They are generally subtidal but may extend as an unbroken transition to the intertidal zone, where they are exposed to the air at low tide. Two main types of reef can be recognised; those where*

[3] Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora – the Habitats Directive

structure is created by the animals themselves (biogenic reefs) and those where animal and plant communities grow on raised or protruding rock. Only a few invertebrate species are able to develop biogenic reefs, which are therefore restricted in distribution and extent."

- Holt *et al.* (1998) page 7 define biogenic reefs as: "*Solid, massive structures which are created by accumulations of organisms, usually rising from the seabed, or at least clearly forming a substantial, discrete community or habitat which is very different from the surrounding seabed. The structure of the reef may be composed almost entirely of the reef building organism and its tubes or shells, or it may to some degree be composed of sediments, stones and shells bound together by the organisms."*

- (UK Marine SAC Projects, 2001a) used the following criteria to define biogenic reefs:
  - *the unit should be substantial in size (generally of the order of a metre or two across as a minimum, and somewhat raised, mainly in order to disqualify nodule like aggregations such as may be formed by S. spinulosa and scattered small aggregations such as occurs with many of the species under consideration);*
  - *and should create a substratum which is reasonably discrete and substantially different to the underlying or surrounding substratum, usually with much more available hard surfaces and crevices on and in which other flora and fauna can grow.*

- Langmead *et al.* (2008) define biogenic reefs as: "*Benthic reefs composed of living organisms including mussels and soft corals that form a biogenically constructed frame, and secondary settling species such as echinoderms and crustaceans".*

The Langmeand *et al.* (2008) definition will be considered throughout this thesis.

2.2.2 *Modiolus modiolus* (Horse Mussel)

Modiolus modiolus (common name: horse mussel; Figure 2.12) is a large bivalve mollusc with a size range of 35 to 200mm (Tyler-Walters, 2007) which generally inhabits the subtidal and lower intertidal region of the northern Atlantic and Pacific oceans (Mair *et al.*, 2000; Tyler-Walters, 2007), usually in a water depth between 5 and 50 m; however individuals have been found up to a depth of 280m (Schweinitz and Lutz, 1976). It is a reef building species and forms thick beds (biogenic reefs) on the seabed in dense populations (Holt *et al.*, 1998).

The mussels attach to the substratum (which can range from large boulders to mud and sand) and to other individuals with byssal threads, forming aggregated clumps (Tyler-Walters, 2007; Rees, 2009c). It is a very long-lived species and animals in reef communities are frequently 25 years old or more (Holt *et al.*, 1998). Although individually *M. modiolus* is a widespread common species, horse mussel beds (patches extending more than $10m^2$ with more than 30% cover are definitely classed as "beds") are limited in their distribution (Rees, 2009c). *M. modiolus* beds become absent or more scarce towards the geographic range limit of the species (Rees, 2009c).

M. modiolus beds generally occur in cold temperate coastal parts of the north-east Atlantic shelf seas, from the Barents and White Seas to the southern North Sea; and is presently absent in Arctic waters (Rees, 2009a)

M. modiolus beds occur in two main physical forms: semi-infaunal reefs, which grade in density and thickness from continuous dense, raised reefs to scattered clumps which may not actually fit the definition of biogenic reefs; and a more unusual infaunal gravel-embedded reef community which can form wave like mounds up to 1 metre high (Holt *et al.*, 1998), or irregular clumps partially buried in soft sediment (Roberts *et al.*, 2004). *M. modiolus* has a very strong structuring influence on the sediments in which reef areas usually occur, and extremely rich associated faunas containing hundreds of species have been found (Holt *et al.*, 1998). Communities associated with *Modiolus* beds are diverse, with a wide range of epibiota and infauna, such as hydroids, red seaweeds, solitary ascidians and bivalves such as *Aequipecten opercularis* and *Chlamys varia* (Rees, 2009c); Figure 2.13. Modiolus beds are often persistent features which build up through time as a result of the accumulation of faecal pellets, shell and trapped sand, and may eventually become disassociated from their original settlement substratum (Rees, 2009c).

Figure 2.13: *Modiolus modiolus* with anemone and brittle stars, Loch Creran

Source: Robert Cook, Heriot Watt University.

The mussels have a stabilising effect on the seabed due the binding effect of the byssal threads which in turn can alter sea floor roughness, topography and acoustic reflectivity (Rees, 2009c).

The habitat created through the aggregation of *Modiolus* beds provides a number of benefits to the marine environment as a whole. In addition to stabilising the seabed, the reefs also provide habitats for a number of marine organisms including sponges, oysters, scallops and seaweeds. Infauna, supported through pelagic-benthic coupling of these filter feeders is enhanced and there are niches for a higher number of crevice-dwelling species, predators and scavengers (Rees, 2009c). Fish make use of both the higher production of benthic prey and the added structural complexity; and several commercially exploited scallop species (*Pecten maximus* (Linnaeus, 1758), *Aequipecten opercularis* (Linnaeus, 1758) and *Chlamys islandica* (O. F. Müller, 1776)) occur in the same habitat (Rees, 2009c); Figure 2.14.

Figure 2.14: *Modiolus modiolus* beds with scallop (*Aequipecten opercularis*

Source: Robert Cook, Heriot Watt University.

2.3 Environmental requirements and geographical range

M. modiolus beds are generally found in areas of moderate to strong tidal currents although beds have been found in more sheltered bays and fjords (Rees, 2009c; Holt *et al.*, 1998). Larvae will settle on a variety of shell and stone substratum, including other *Modiolus* shells, and studies have suggested that the best refuge from predation is in the byssus thread of established *Modiolus* aggregations (Roberts, 1975). Although some form of hard substratum is usually required for initial formation of *Modiolus* beds and reefs, they are capable of forming on a variety of sedimentary bottoms such as mud or coarse mixed sediments (UK Marine SAC Projects, 2001b).

M. modiolus is an Arctic-Boreal species, with a distribution range covering the seas around Scandinavia (including Skagerrak and Kattegat) and Iceland south towards the

Bay of Biscay (Rees, 2009c), the White Sea (Myagkov, 1975; Flyachinskaya and Naumov, 2003), (although they are thought to be absent from the Baltic Sea (Brown, 1984)), Canada and North America (Brown, 1984; Schweinitz and Lutz, 1976), although dense aggregations appear to reach their southerly limit around the British Isles suggesting that they may be susceptible to a long-term rise in summer water temperature (UK Marine SAC Projects, 2001b).

2.3.1 Factors influencing the Distribution of *Modiolus modiolus* Beds

Consideration of the environmental factors/variables that influence distribution of *M. modiolus* beds was required in order to address our research questions. Of the factors principally influencing bed distribution: temperature, depth, salinity, water movement, water quality and substrate are considered to be important (UK Marine SAC Projects, 2001b).

Temperature: *M. modiolus* is an Arctic-Boreal species, with the dense aggregations defined as beds, reaching their southerly limit around the UK (UK Marine SAC Projects, 2001b). In 2009, the National Oceanic and Atmospheric Administration (NOAA) World Ocean Atlas (WOA) indicated that average annual ocean bottom temperatures ranged from 6^{o}C to 12^{o}C in the shelf waters around the UK (excluding the extended UK Economic Exclusion Zone (EEZ) to the north and west; Figure 4.1) (NOAA, 2009). Studies on the effects of climate change on benthic communities in the UK suggest inhibition of recruitment at southerly limits as a result of increased ocean temperatures (Hiscock *et al.*, 2004), while increased colonisation of northern areas such as Svalbard, Norway and parts of the Arctic may be expected (Rees, 2009b); suggesting a long term susceptibility to increased ocean temperature (Rees, 2009b). Literature on the upper thermal limits of *M. modiolus* beds is limited, but data suggest that it is lower than that of *Mytilus edulis* (Bayne, 1976); British *M. edulis* have an upper sustained thermal tolerance limit of about 29°C (Almada-Villela, 1984; Read and Cumming, 1967). Studies have shown that horse mussels may also under-go seasonal temperature compensation through the maintenance of high concentrations of rate-limiting enzymes of intermediate metabolism (quantitative strategy) when exposed to cold temperatures whilst also maintaining high levels of protection against oxidative stress and protein denaturation (Lesser and Kruse, 2004). *M. modiolus* are known to be sensitive to changes in temperature and salinity, which makes them dependent on deeper subtidal waters (Halanych *et al.*, 2013).

Depth: *M. modiolus* beds are generally restricted to depths between 5 and 50 m in UK waters, occurring at shallower depths in more northerly latitudes (Anwar *et al.*, 1990; Wildish and Fader, 1998), although deeper aggregations have been found in water depths over 80 m in Nova Scotia (Wildish and Fader, 1998) and individual specimens have been recorded at depths up to 280 m (Schweinitz and Lutz, 1976).

Salinity: Generally *M. modiolus* beds are adapted for full salinity areas, where fluctuations are minimal (Pierce, 1970). Established tolerance limits of 27-41‰ for *M. modiolus* based on ventilation behaviour and byssus formation have been reported (Pierce, 1970).

Water Movement: The build-up of sediment on dense aggregations of *M. modiolus* is an important factor in the establishment and stability of the beds. Sediment transport is therefore strongly influenced by water movement; with the majority of beds being found in areas of moderate to strong tidal currents (UK Marine SAC Projects, 2001b).

Water Quality: *M. modiolus* beds are found in a variety of turbid and clear water conditions (UK Marine SAC Projects, 2001b) and is reported to have a similar tolerance of oxygen deficiency and hydrogen sulphide to *Mytilus edulis* (UK Marine SAC Projects, 2001b).

Substrate: Although there is a requirement for some form of hard substratum for initial formation, *M. modiolus* beds are capable of forming on a variety of sedimentary types, including muddy substrata in sealochs to coarse mixed shelf sediments containing stones and shells (UK Marine SAC Projects, 2001b)

2.4 Threats

Potential impacts to *Modiolus* reefs are generally more significant from industries which come into direct contact with the seabed such as fishing, dredging and construction/installation; although residual impacts from non-direct sources may also occur, for example contamination from discarded chemicals and spills or smothering as a result of increased sedimentation.

The impacts of the fishing industry on *Modiolus* beds is probably the most well documented out of all the potentially impacting marine industries, for example with scallop and queen scallop dredging being implicated in the significant reduction in density and extent of the dense *Modiolus* beds throughout the Irish sea (UK Marine SAC Projects, 2001b; Roberts, 1975; Roberts, 2003; Roberts *et al.*, 2011; Roberts *et al.*, 2004; Cook *et al.*, 2013). Fishing gear particularly, trawling and dredging physically damage the seabed and any reef structures, either removing them from the seabed completely, or significantly damaging them. As *M. modiolus* is a slow growing organism, damage to the reef caused by fishing may be long term and significant.

Recruitment of *M. modiolus* spat is slow and sporadic (Flyachinskaya and Naumov, 2003), making the potential recovery from damage a long process, and in fact several years can pass without recruitment occurring (Halanych *et al.*, 2013). The larval phase can be up to 6 months, and therefore there is the potential for long distance dispersal (Halanych *et al.*, 2013).

At present the impacts arising from many offshore industries such as wet renewable (wave and tidal) devices or aquaculture for example have not been quantified; and no specific studies have been identified. The number of Environmental Impact Assessments (EIAs) that have been carried out for example for wet renewables, is limited as development of demonstration sites for these forms of renewable energy devices are still in their infancy. In Appendix D an initial impact assessment of potential renewable developments on *M. modiolus* beds is provided.

The horse mussel is also known to be a bio-accumulator of contaminants such as heavy metals in spoil disposal areas but the effects on condition, reproduction and mortality rates are at present unknown (UKBAP, 2000).

2.5 Potential Interactions with habitat arising from Marine Spatial Planning and Management

The importance for policymakers and managers to transition from managing sectoral activities toward ecosystem-based management (see Chapter 1); ensuring the activities and pressures on ecosystems are managed; is acknowledged by Crowder and Norse (2008). This will be achieved through the implementation of Marine Spatial Planning; and an emerging tool to support the implementation of an ecosystem based approach to management; including the creation of a Marine Protected Area network (see Chapter

1). However, decisions still need to be made as to how these plans are going to be implemented and what method of "zoning" will be applied.

From a PMH point of view, zoning schemes which put weight on environmental legislation and conservation will be most complementary – however, these methods may not necessarily take all economic activities into account.

Work currently being undertaken by McWhinnie *et al.* (in progress) examines the implications of zoning schemes published by Boyes *et al.* (2007) and Day *et al.* (2008) on PMFs in Scottish waters. These zoning schemes are based on all marine legislation in the case of Boyes *et al.* (2007) and on environmental legislation alone in the case of Day *et al.* (2008). Results to date indicate that presently there are no suitable published marine spatial planning frameworks that comprehensively manage the marine environment, its conservation aspects and activities (Mcwhinnie, Pers. Comms). This would therefore suggest that marine spatial planning, at present provides inadequate protection for Priority Marine Habitats.

2.5.1 Management Measures

From the above literature review, it can be seen that in general, a number of studies have been conducted on the ecology and biology of *M. modiolus* particularly in the 70's and 80's (Brown, 1984; Comely, 1978; Davenport and Kjørsvik, 1982; Mann *et al.*, 1987; Pierce, 1970; Read and Cumming, 1967; Schweinitz and Lutz, 1976; Seed and Brown, 1975; Seed and Brown, 1978), with more contemporary studies (90's to present) focussing on the habitat form (Cook *et al.*, 2013; Elsäßer *et al.*, 2013; Fariñas-Franco *et al.*, 2013; Lindenbaum *et al.*, 2008; Mair *et al.*, 2000), as environmental legislation set a precedent and *Modiolus modiolus* beds, as defined as a biogenic reef, were afforded protection under the EU Habitats Directive and the MSFD in UK waters.

Through such frameworks, the protection is often defined through the more traditional route such as the development of protected areas, e.g. Special Areas of Conservation (SAC; Habitats Directive) and Marine Protected Areas (MPA; MSFD). Current management measures for the protection of *Modiolus modiolus* beds within protected areas (SACs) are site specific, and generally depend on the inclusion of other “biogenic reefs” within the particular site. Potentially impacting activities within the sites are subject to conditions of operation (e.g. fisheries zoning plans) and the use of EIAs is a common management tool, in which impact mitigation is addressed.

At present the Scottish Government is still in the process of defining the management options and potential measures for the newly designated MPAs which will ensure that measures will further the achievement of the conservation objectives whilst minimising any impacts on current activities. Measures will be again site specific, for example, the setting of an order under the Inshore Fishing (Scotland) Act 1984 to implement a management measure for a certain type of fishing in a MPA, the provisions for a Marine Conservation Order (Scottish Government, 2013) or activity Environmental Impact Assessments (EIAs).

Figure 2.15 outlines the Scottish Governments' process for selecting appropriate management options. At present there is a lack of information on the specifics regarding management selection and how these processes will be determined and assessed. It is stated (Scottish Government, 2013) that the "sensitivity matrix" for example, will be based on the work undertaken by Tillin *et al.* (2010) which provides an assessment of the sensitivity of marine features of conservation interest to physical, chemical and biological pressures; and combined with a developed activities-pressures matrix (no formal reference available (Scottish Government, 2013)).

The Scottish Government provides a logical method for the selection of management measures. However, the proposed measures, do not appear to be particularly novel and although site specific management may appear to be the best option, this can be both time consuming and costly – and may not actually provide the best protection whilst also allowing for sustainable use of the area. At present, there appears to be little research or evidence available addressing the possibility of non-site specific management measures (broad scale/area management).

In addition, there seems to be no precedent set for dealing with the inherent scientific uncertainty that surrounds setting conservation management targets (Agardy *et al.*, 2003) with regard to management within an MPA network. For example, for an MPA network to be coherent (under the MSFD) should all MPAs be managed separately, or should they be managed as a network?

Unfortunately, very few ecosystems are well enough understood to allow for accurate predictions with regard to how successful the management measures will ultimately be (Agardy et al., 2003). Therefore, there is a requirement for the development of a rationale for evaluating management effectiveness (Pomeroy et al., 2005). This has been acknowledged with this thesis, and led to the development of an initial predictive management tool (see Chapter 6).

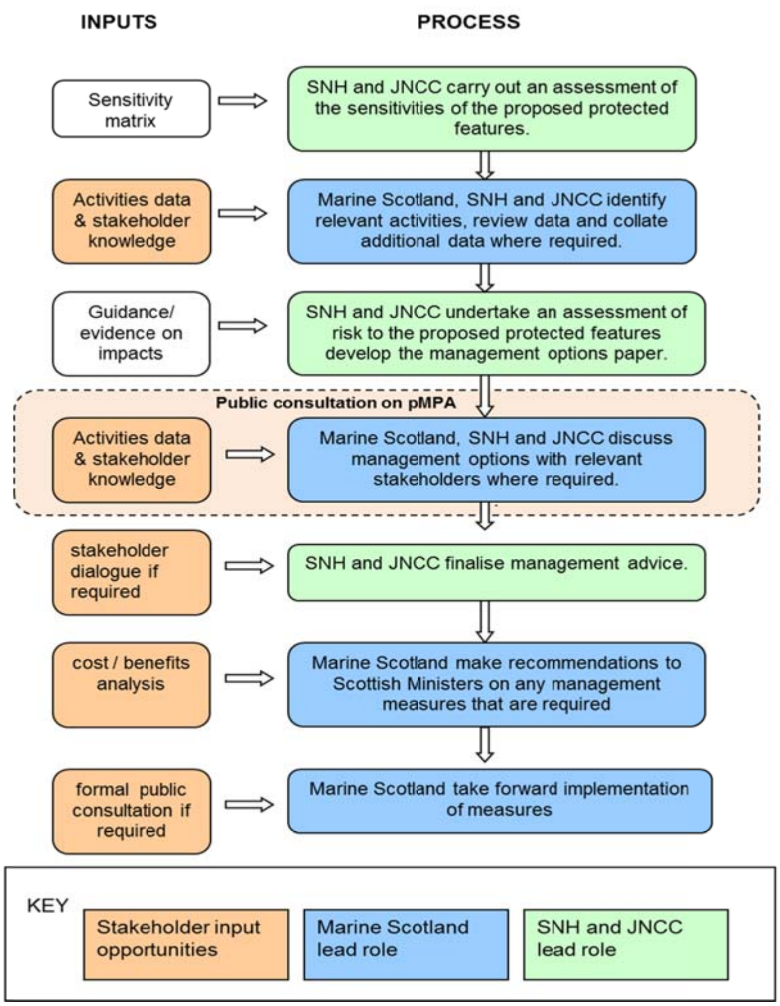


Figure 2.15: Scottish Government Management Measure Process

Source: (Scottish Government, 2013)

It has been suggested that proposed management measures for tidally swept communities (including *Modiolus modiolus*) should include (Scotlink, 2013):

- spatial planning of mobile fishing gear and aquaculture, which may include closed areas;
- mapping of community locations; and
- improved long-term monitoring, research and conservation biology including recovery studies.

However, it appears that the suggested management measures outlined above are slightly vague and may be missing the mark when it comes to full protection of the beds and addressing the lack of knowledge about the ecosystem. As it is acknowledged that as the communities are long-lived and have potentially restricted recruitment, it would therefore seem pertinent to try to clarify what the implications of this lack of knowledge may have on management. It is noted that for mobile species, one such management measure is the protection of movement corridors, therefore allowing for connectivity of important sites. It is felt that this is also an issue that should be considered for habitat forming species and is addressed within this thesis (see Section 2.6 and Chapter 7)

The understanding of habitat connectivity would contribute to the selection of suitable management measures by allowing decisions to be made from a network point of view. Plans would be able to incorporate these management measures and be able to assess which sites can be managed together. In addition, this would also lead to the possibility of creating marine spatial plans that were transboundary (for example at a European level) allowing for combined management of a European MPA network in the event of connected habitats, potential climate change scenarios (see Chapter 5) and through the possibility for habitat restoration.

2.6 Habitat Connectivity

Particle tracking of *M .modiolus* larvae at sample locations within the Irish Sea were carried out in collaboration with Bangor University. Work has also been carried out by Marine Scotland (Gallego *et al.*, 2013) into the potential connectivity of Marine Protected Areas in Scotland. Details of which are discussed in Chapter 7.

The genetic diversity and genetic connectivity of PMHs is not very well studied and as a result will be considered for *M. modiolus* within this thesis. The phylogeography of *M. modiolus* was studied by Halanych *et al.* (2013) for specimens collected from the North Atlantic and Pacific Oceans. Their study however, does not indicate whether these samples were collected from beds, or were from individual specimens collected in seabed surveys. Their analysis involved the screening of samples for the partial mitochondrial gene cytochrome oxidase subunit 1 (CO1). Results showed that the North Atlantic and Pacific populations are genetically distinct, forming two distinct clades with no shared haplotypes. It is thought that *M. modiolus* likely expanded from the Pacific into the Atlantic and calculations indicated that it would have taken *M. modiolus* approximately 2.6 to 3.5 MYA to reach the 8-11% divergence observed between the two populations.

Chapter 7 of this thesis examines the CO1 gene variability further and explores the possibility of examining connectivity at a finer scale through the use of more sensitive microsatellite markers.

2.7 Summary

Following a review of available scientific literature on the known distribution of *Modiolus modiolus* and the factors that influence its distribution, with regard to the aims of this research project, *Modiolus modiolus* was chosen as the study subject based on the factors of data availability, collection and identification as outlined in Section 2.2.

With regard to species distribution modelling, the quality and availability of distribution data are paramount. The collection of data is discussed in Chapter 3. In addition, the relationship between the distribution of the target species and its environment is particularly important within a modelled setting. For that reason sessile organisms, like *M. modiolus* (and the beds they create) are particularly desirable due to the ease of locating occurrence records and marrying them with the available environmental data layers (Marshall, 2011).

In addition, given their marine conservation status, data availability is generally good with targeted surveys providing reliable and recent distribution data sets; with the marine conservation status alone making them worthy of scientific research.

From a genetic point of view (see Chapter 7) *M. modiolus* is considered as a good study species. In particular, following collection of species, the removal of adductor muscle tissue for DNA extraction is straight forward given the large size of the individual animals. Furthermore, the lack of data or information on the genetics and connectivity of *M. modiolus* beds makes them again a suitable candidate for further study.

Chapter 3. Distribution and Loss of Habitat: Exploring Data and Methods

3.1 Introduction

In this chapter the types of methods that could be employed to examine the research question outlined in Chapter 1 is investigated. Consideration is given to the types of available data and the limitations of both the methods and the data. The choice of methods that best inform marine environmental policy, and the question of whether there is sufficient data to make projections about the impacts of climate change are addressed.

Understanding to what extent a habitat or species has been lost – or more importantly, may be lost - is a crucial step in defining and monitoring Good Environmental Status (GES) as part of the Marine Strategy Framework Directive (MSFD) process and creating sustainable marine plans. The creation of Priority Marine Habitats or Priority Marine Features) (see Section 2.1 and Appendix B) has led to SNH identifying a list of key species and/or habitats that are "*considered to be of greatest marine nature conservation in Scottish territorial waters*" (SNH, 2011b). The purpose of creating this list will enable identification of the features for which it will be appropriate to devise new area-based management strategies, such as MPAs and MSP; features for which this type of management is not appropriate; and features of importance to the functioning of marine ecosystems more widely (SNH, 2011b).

One of the objectives of the MSFD is to classify areas or habitats that are of GES and which will need to be improved in order to achieve this. However, the methods have yet to be defined for how the assessment for the descriptors (see Appendix A, Section

A.1.3) will be carried out. Descriptor 1 requires that biological diversity is maintained and that the quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic and climatic conditions (DEFRA, 2011d). This therefore means that the policy maker will need to decide what will be used as the baseline against which assessment criteria will be categorised.

However, the issue is that there is limited understanding of the baseline condition of some habitats and species; and therefore how can GES be assessed if it is unknown what state the habitat/species “should” be in? This is being classed as the "reference condition" of the habitat (Hill *et al.*, 2012). Habitat and species destruction has occurred in UK waters as a result of historical and present day industrial activity such as the destruction of the *M. modiolus* beds in Strangford Lough, Northern Ireland as a result of scallop dredging (see Appendix C for a summary of the Strangford Lough case study (Roberts *et al.*, 2004; Roberts *et al.*, 2011)). Do we therefore assume the baseline/reference condition of this habitat to be how the beds are now, therefore requiring minimal action to achieve GES; or do we need to determine how they were prior to the dredging and to regenerate/restore them in order to achieve GES? This is still an area that is to be addressed within the MSFD.

3.1.1 Climate Change

It is widely accepted that the natural distribution patterns of organisms are primarily driven by their environmental requirements (Pearson *et al.*, 2002); and that climate change is having an impact on this natural distribution through range expansion and contraction; it is therefore expected that future climate change will have a significant influence on the distribution of species (Pearson and Dawson, 2003). The effect climate change has on geographic distribution is often assessed in terms of potential envelopes/spatial niches shifting in altitude, longitude or latitude; and this influence could potentially threaten biodiversity and conservation of the species (del Barrio *et al.*, 2006).

3.1.2 Aims and Objectives

- ***Research Overview:*** *The knowledge gained will enable decision makers to use publically and freely available modelling techniques in order to view the potential movement of the species in relation to* *environmental change and incorporate this information, together with other scientific data into the MSP and MPA management.*

Key tasks:

- *Identify current and historical distribution data and GIS shapefiles*
- *Investigate how the distribution of the feature can be modelled*

This study identifies a number of data resources which document the distribution of individual *M. modiolus* specimens and beds. These data will be mapped using the ESRI ArcGIS system and a suitable species distribution modelling technique will be identified and applied to determine what environmental factors influence the distribution of *M. modiolus* and whether specific climate change scenarios/events influence this distribution. The study will provide an outline of available modelling techniques, which, when used correctly may provide information on the potential movement of the species in relation to environmental change. Modelling techniques and climate change scenarios will also be applied to other species and habitat forming species.

In addition, it was important to identify data sources, for species data, environmental parameters and the modelling software that are freely available[4] either, on or offline in order to make this research functional outside this research project.

3.2 *Modiolus modiolus* Distribution Data

3.2.1 Methods: Data Collection and Processing

Gaining a thorough understanding of what kind of data are available on the chosen study subject; and it's quality, was the initial stage of selecting our chosen modelling methodology. If suitable data were not available, certain models would/could not be selected for use.

Although it has already been decided to focus on the *Modiolus modiolus* beds as the study subject – it is useful to examine the availability of individual *M. modiolus*

[4] Freely available: meaning data/software is free of charge for non-commercial use e.g. governmental or research. Some data are subject to licence conditions.

specimen distribution data to confirm applicability of using the bed distribution within the chosen methods.

In addition, creating a baseline data collection of all known distribution of our study subject contributes to the baseline understanding of the species and its geographical range.

Collection methodology, data sources and data formatting and processing are presented in Appendix E for "presence only" and "presence/absence" data. Data quality is discussed in Section 3.2.3.

3.2.2 Results: Mapping Data

The collected and formatted presence only data were imported into ArcMap v10.1. The data were separated by suitable yearly intervals and mapped (see Figures 3.1 to 3.9). The maps show the distribution of individual *M. modiolus* specimens around the UK. The point symbols represent an individual *M. modiolus* specimen and not a "bed". The data illustrates location of specimens, by year group, collated from the data sources outlined in Appendix E; Table E.1.

The distribution shows concentrations within the North Sea, Irish Sea, Shetland, English Channel and West of Scotland. No clear distribution pattern was noted for the distribution of individual *M. modiolus* specimens throughout the geographic area. In addition, historical through to present data showed no notable change in distribution.

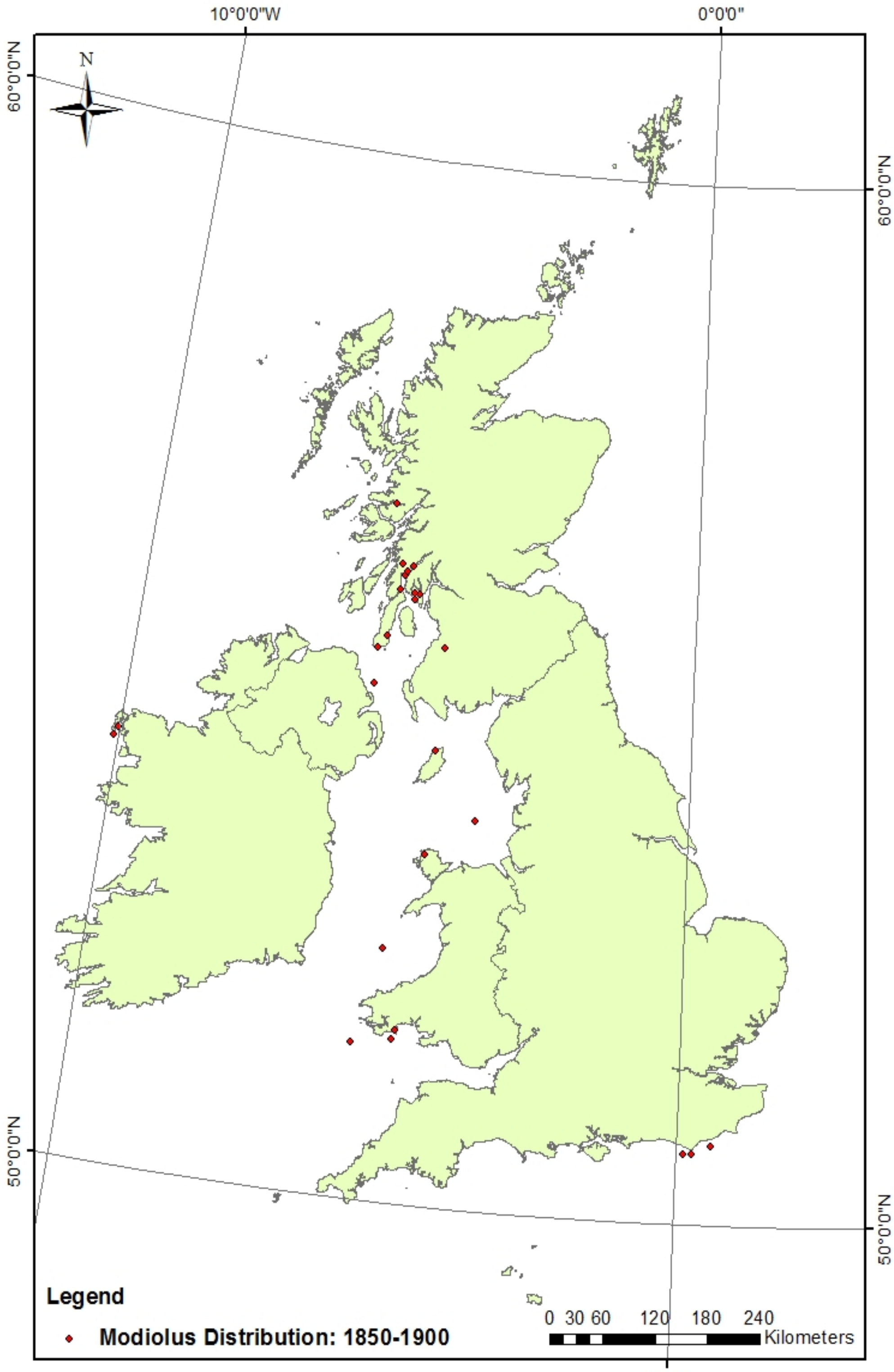


Figure 3.1: Individual *Modiolus modiolus* distribution 1850 - 1900

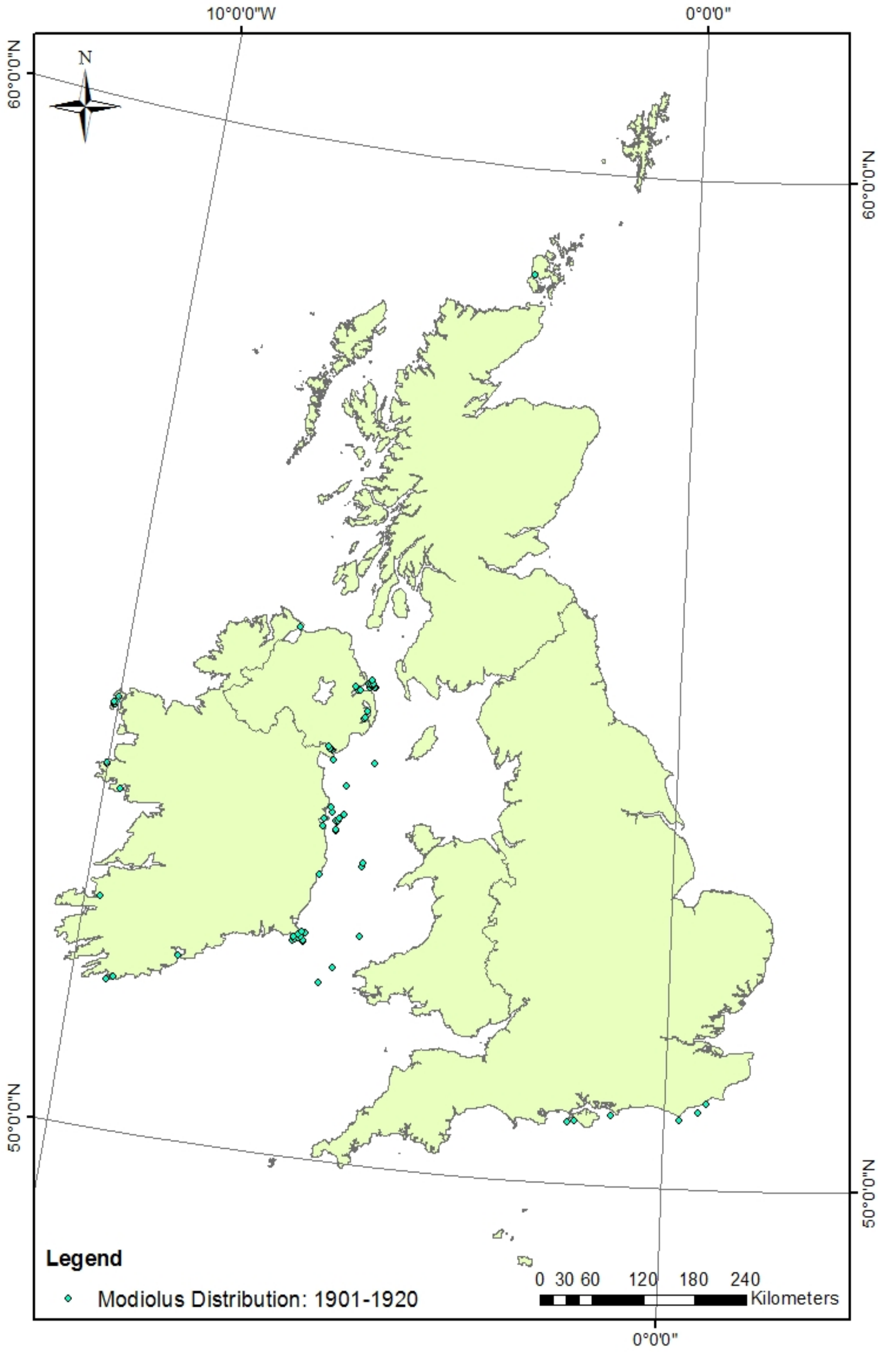


Figure 3.2: Individual *Modiolus modiolus* distribution 1901 - 1920

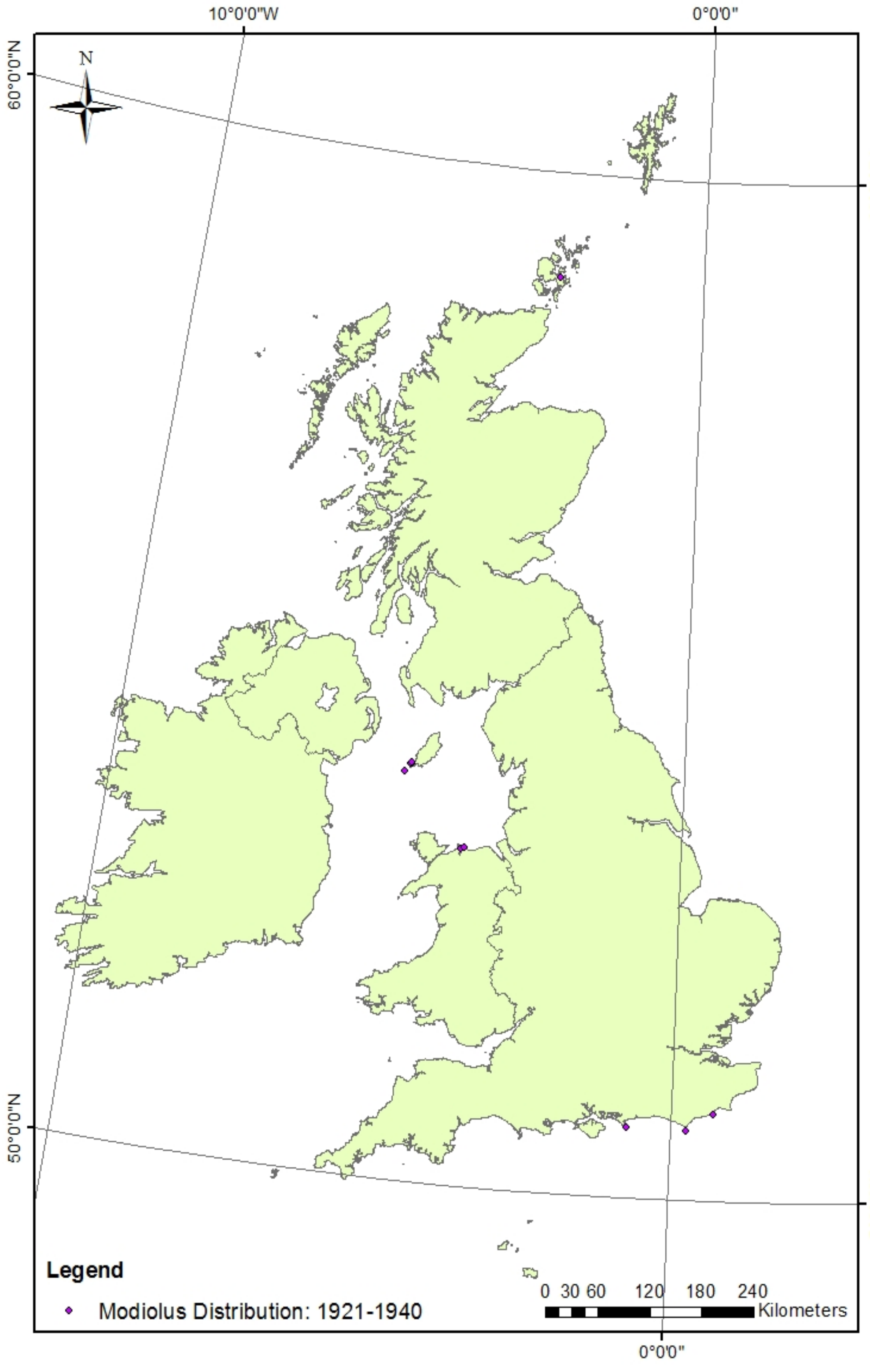


Figure 3.3: Individual *Modiolus modiolus* distribution 1921 - 1940

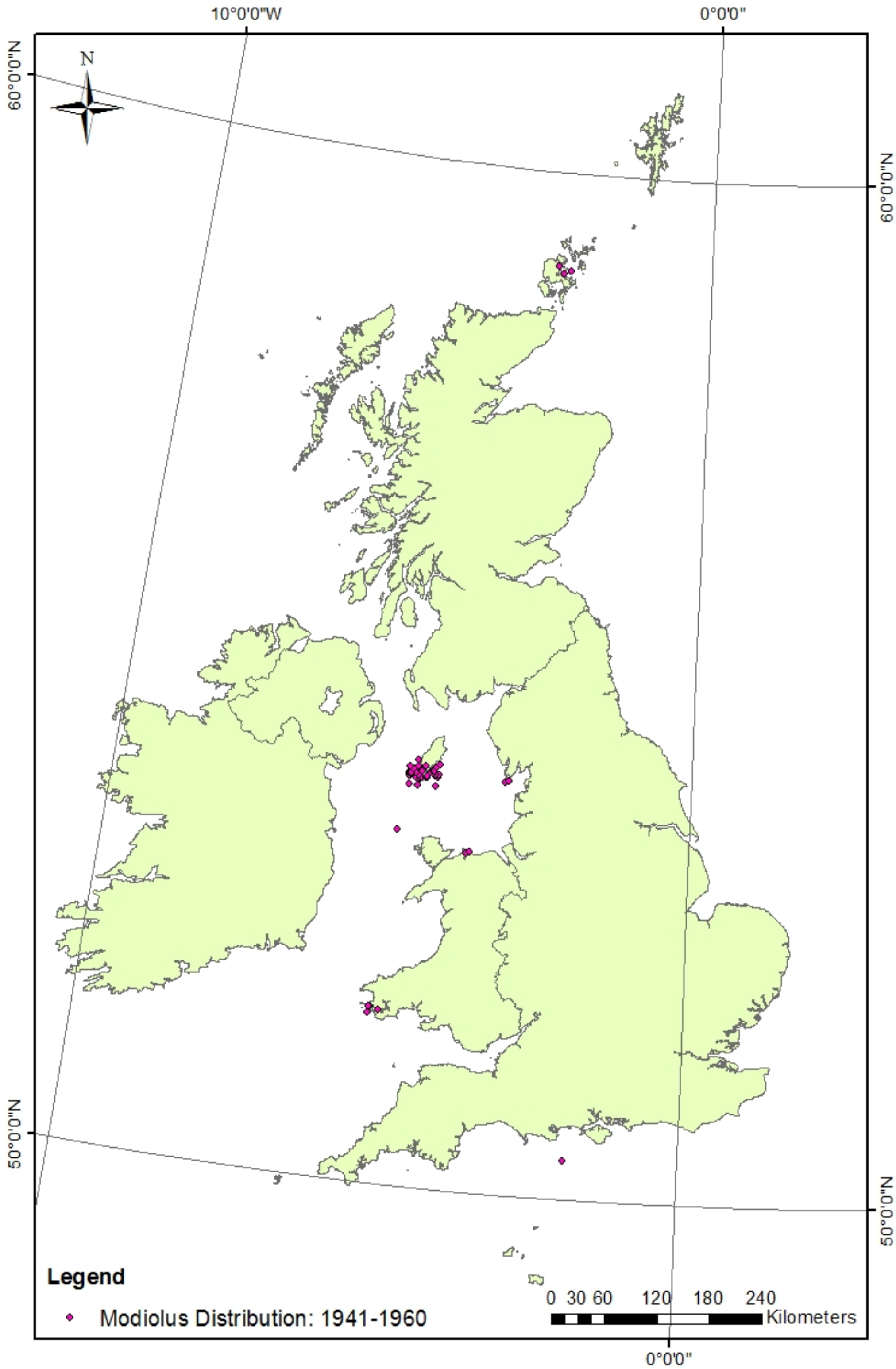


Figure 3.4: Individual *Modiolus modiolus* distribution 1941 - 1960

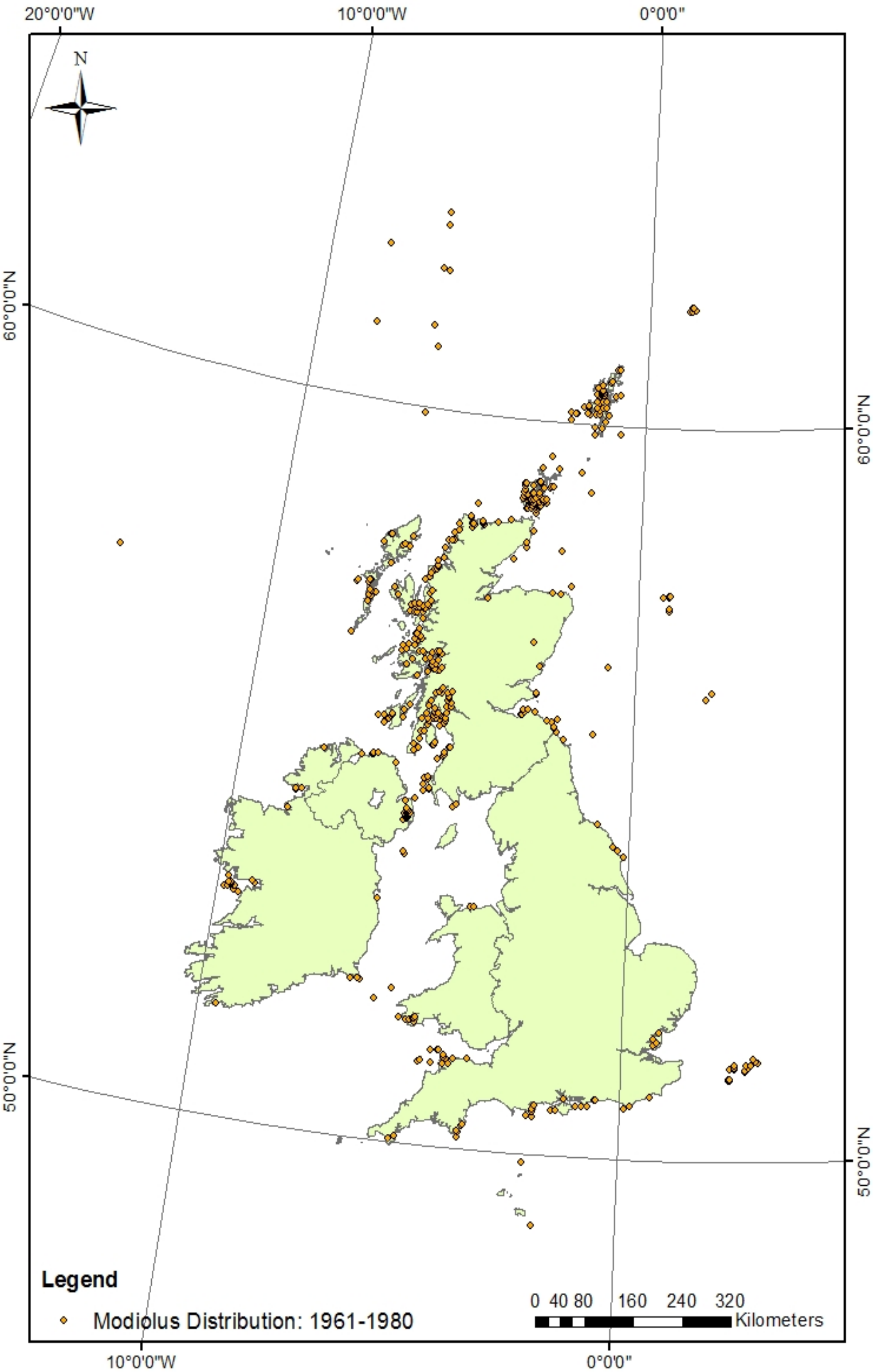


Figure 3.5: Individual *Modiolus modiolus* distribution 1961 - 1980

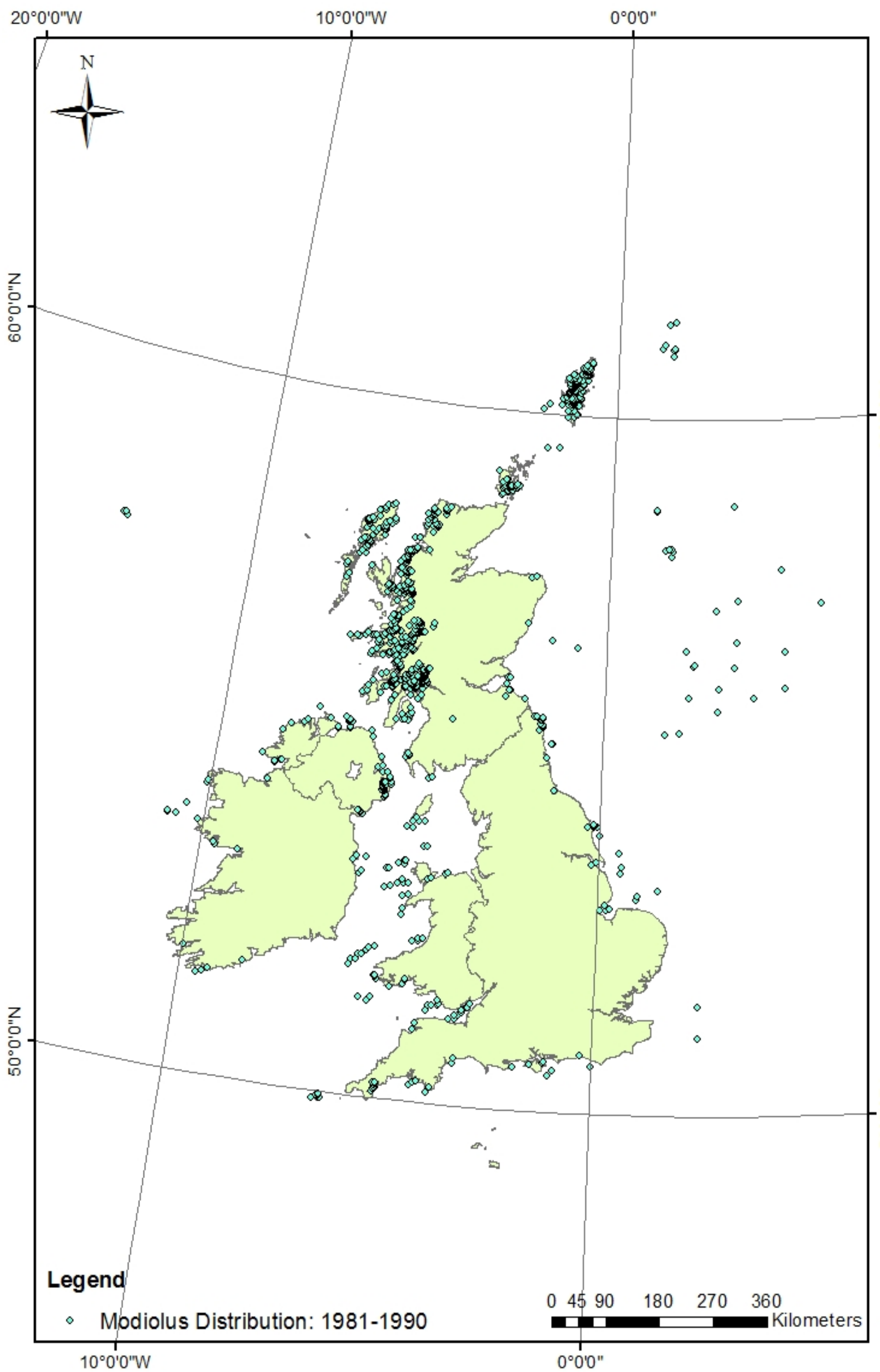


Figure 3.6: Individual *Modiolus modiolus* distribution 1981 - 1990

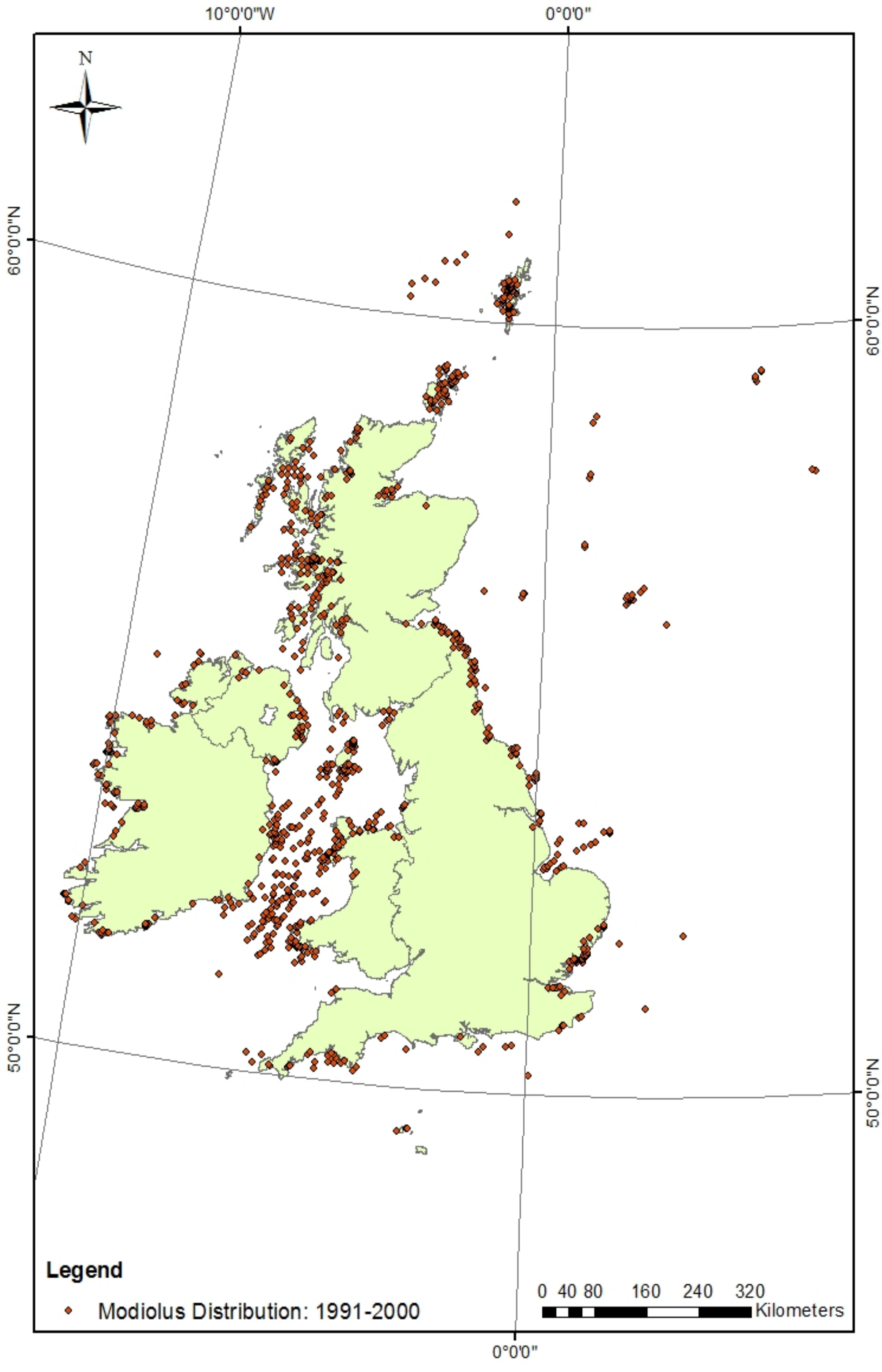


Figure 3.7: Individual *Modiolus modiolus* distribution 1991 - 2000

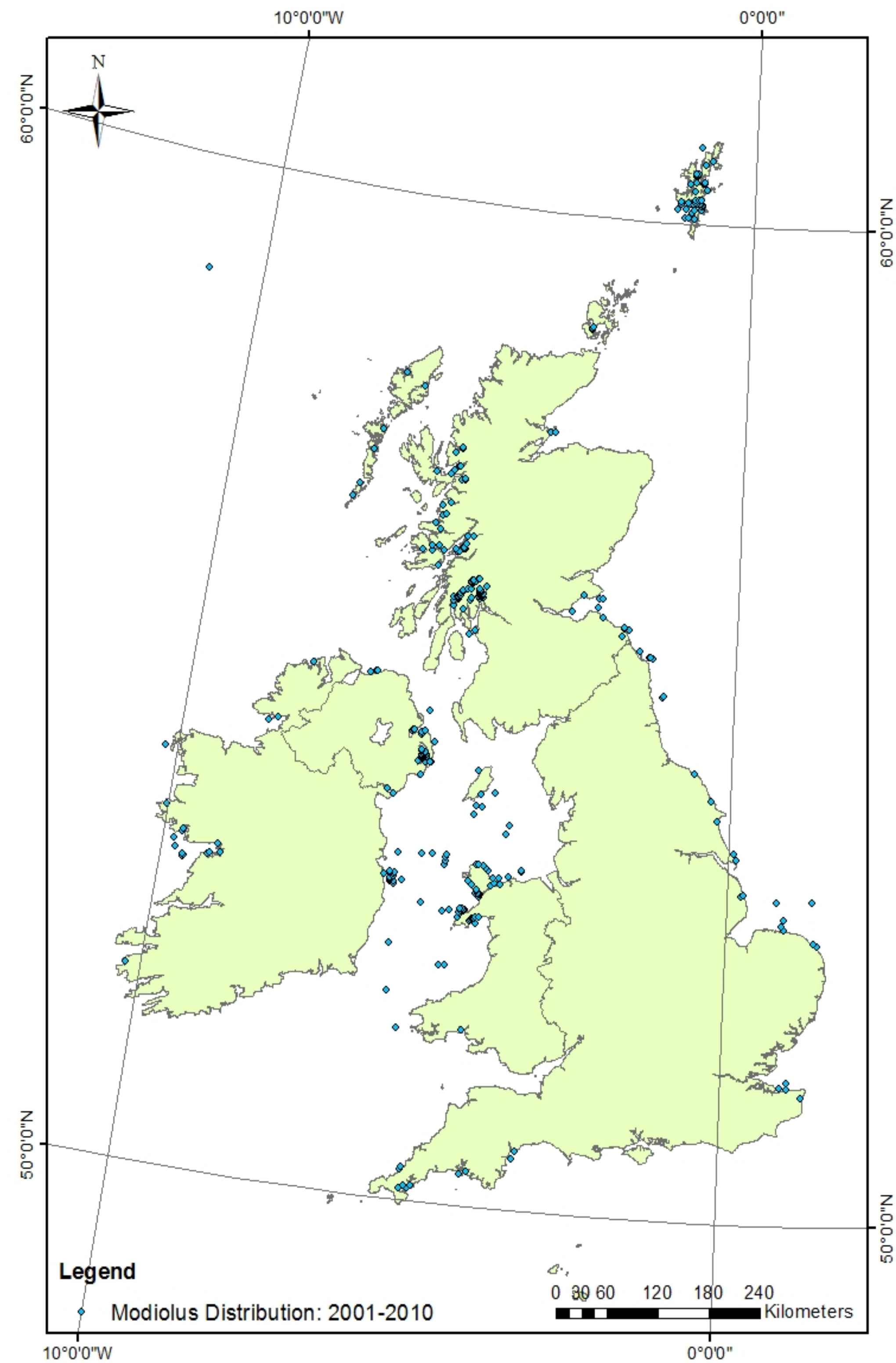


Figure 3.8: Individual *Modiolus modiolus* distribution 2001 - 2010

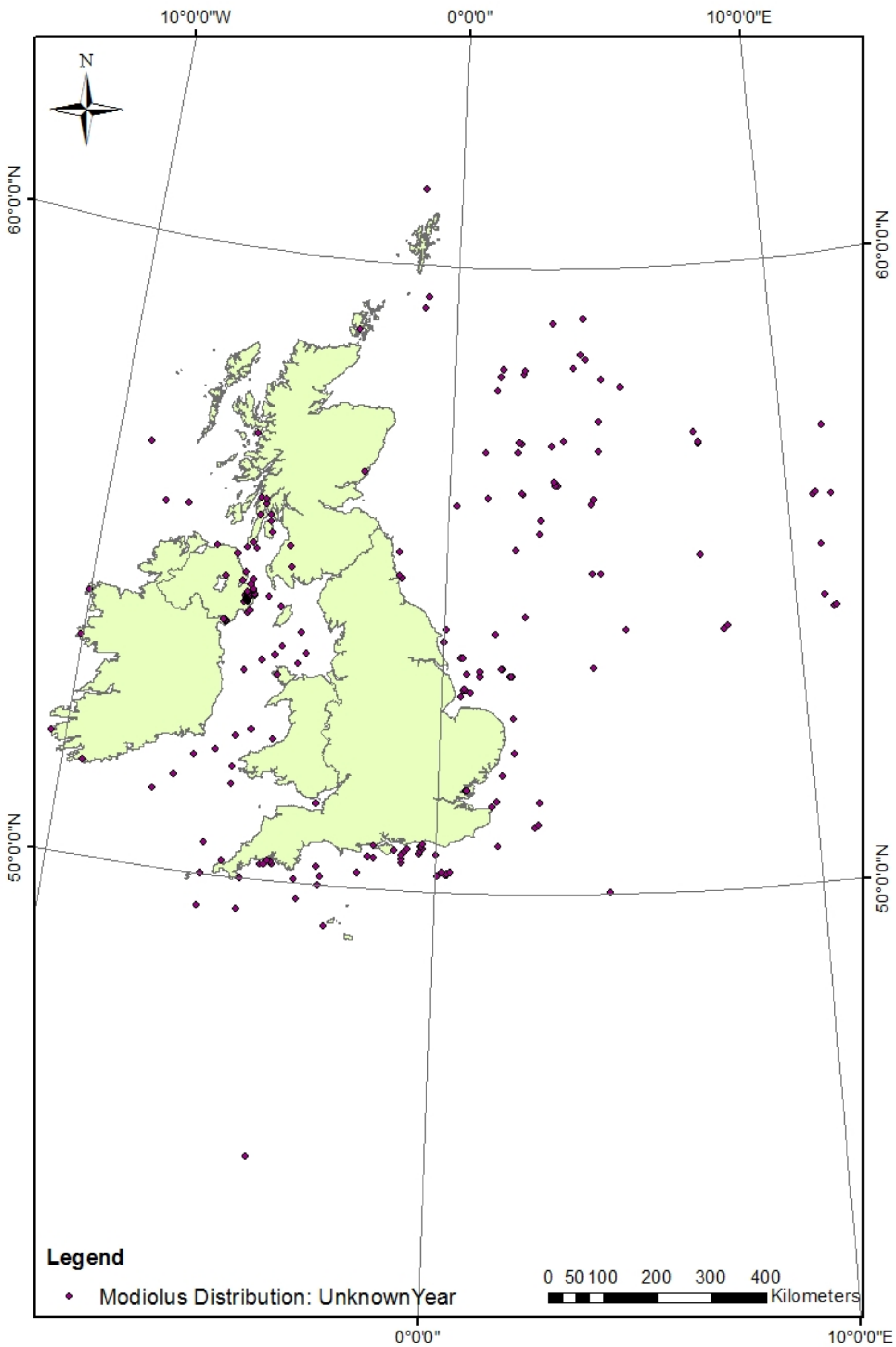


Figure 3.9: Individual *Modiolus modiolus* distribution - unknown year group from data collection (no date)

3.2.3 Discussion: Data Quality

Data quality was taken into consideration during data collection. Due to the required mapping process for this exercise, only one major data quality criteria existed: location information. This location information may have been recorded in a co-ordinate, grid code or descriptive format, depending on data source and age. Data formatting is discussed in Appendix E. It was decided that based on the large volume of data collected, priority would be given to data sets where Longitude and Latitude data were available (either before or after formatting). A number of specimens were accompanied by descriptive location information or bearing and distances. Data with no coordinates or grid references were therefore discarded.

Although we were able to map the distribution of individual *Modiolus* specimens from 1850 to 2011, unfortunately, the mapped distributions do not necessarily provide a well-defined representation of the change in individual specimen distribution over the 161 years depicted. A number of reasons have been surmised and include:

Sampling effort: This is probably the biggest influence on the mapped distribution of individual *M. modiolus*. Marine surveying effort could be assumed to be "ramping-up" in the 1980's and 1990's when environmental legislation and conservation management were becoming more important. Concentrations of *Modiolus* in the North Sea from the 1980's onwards may be attributed to oil field targeted surveys. The reduced number of specimens recorded in the 1920's to 1940's may be because of reduced survey efforts due to World War II.

Survey techniques would have improved over time and with this, the amount of time spent at sea increased. In addition, more remote or deeper areas can be surveyed allowing for a wider distribution to be recorded.

Incorrect Taxonomy: There is some speculation as to whether specimens recorded in the English Channel are in fact *Modiolus adriaticus* and not *M. modiolus* (W. Sanderson; Ivor Rees Pers. Comm. 2012). Historical samples, if available for these areas would have to be further examined to ascertain correct identification.

Anthropogenic pressures: As with any marine species, reduction from a particular area over time can potentially be attributed to anthropogenic pressures such as fishing; aggregate extraction and energy production (see Section 2.4 for more details).

3.2.4 Conclusions: Limitations and Selection of Data

Following review of the “presence only” and “presence and absence” data sets available, it became evident that use of these data within the modelling method would not be suitable. The main reason for not continuing with the use of these records was based on the fact that these records only represented occurrences of individual *M. modiolus* specimens. When mapped (Figures 3.1 to 3.9 and Appendix E), these individual specimens illustrated a wide ranging geographical distribution, in comparison to the data specifically displaying the *M. modiolus* beds. Following mapping of these data it was confirmed that even though the occurrence of *M. modiolus* individuals is wide spread the occurrence of *M. modiolus* beds are not; as the beds are subject to a more specific set of environmental requirements. It was therefore concluded that modelling the individual species would not best represent the “sensitive environmental feature” and would not provide the best representation of the use of this model as a conservation management tool. Therefore it was concluded that only the *M. modiolus* bed occurrence data would be used within the model. This principle has also been acknowledged by work by Ross and Howell (2012) and Howell *et al.* (2011).

In addition, as can be seen in the maps presented in Appendix E, clearly there are errors in the presentation of some of the distribution points, e.g. points occurring on land. In this instance it could be based on input error in the database or a clash in co-ordinate systems within the GIS programme. In most cases, only latitude and longitude data were provided (i.e. no co-ordinate system information) – therefore, these data were incorporated into GIS using the co-ordinate system set at time of input; in this case WGS 1984 UTM Zone 31N. This was also a consideration with regard to the data accuracy of the individual specimens as it is assumed that there is no positional accuracy of the sample sites at sea prior to the 1980’s.

Presence vs. Presence/Absence

There are obviously arguments presented for the use of both "Presence only" and "Present/Absent" data when considering a species distribution model and selection of a specific model will be dependent on the availability of certain usable data sets.

Brotons *et al.* (2004) conducted a study to assess the difference between a presence only model and a presence/absence model (breeding birds) on the output from the models. Their results showed that the presence/absence model predictions were more accurate and that these types of data enhanced model calibration. In addition, results suggested that these presence/absence models may be particularly more important for wide-ranging and tolerant species and that species with less restricted ecological requirements were modelled less accurately than species with more restricted requirements, regardless of which model type was selected. They conclude that if absence data are available, methods using this information should be preferably used in most situations (Brotons *et al.*, 2004) however, alternatives are available, e.g. pseudo-absences (Elith and Leathwick, 2009; VanDerWal *et al.*, 2009).

A criteria for the selection of pseudo-absence data were discussed by VanDerWal *et al.* (2009) in which they conclude that spatial extent should be considered when selecting where pseudo-absence data are selected and that species distribution modelling exercises should start with an exploratory evaluation of which selecting criterion for pseudo-absence data best suits the model, the species data (biologically meaningful) and the location (VanDerWal *et al.*, 2009).

As outlined above, the use of presence/absence data was not possible for the selected dataset, as surveys for *M. modiolus* beds tend to be very site specific in terms of their scope. In addition, it was concluded that *M. modiolus* beds are not wide ranging and potentially have a fairly restricted ecological niche (see Chapter 2), therefore it was concluded that the use of a presence only model (with pseudo-absences) would be appropriate for the modelling of *M. modiolus* beds.

The criteria regarding selection of pseudo-absences (VanDerWal *et al.*, 2009) were taken into consideration when selecting and using the models as discussed in Section 3.3 and Chapter 4.

3.3 Identification and Preparation of Species Distribution Model

3.3.1 Model Selection

Elith and Leathwick (2009) carried out an evaluation of Species Distribution Modelling (SDM) methods and their key features, which provided an overview of model categories. Based on this evaluation an online search for existing freely available modelling software was carried out. Some software available was considered more suitable than others, and an overview of the evaluation and selection process is provided in Table 3.1.

As this study is particularly interested in the use of SDM as a conservation management tool, we were primarily concerned with the ease of use of each model interface along with model reliability acceptance from an ecological and policy point of view. Elith and Leathwick (2009) suggest that if the modeller is inexperienced, has limited time and resources or that the modelling attempt is a “one-off”, then selecting a modelling method based on a user-interface-driven program is the safest option. This principle is acknowledged and leads to the selection of the model and interface used in this study.

It should be noted that the decision was made to base the SDM on pre-existing and developed interface software, rather than existing or new algorithms in order to demonstrate how SDM can be utilised by non-statistical modellers. Complicated model design and development would not provide the type of benefit to external parties as outlined as the overall aim of this project. A number of trade-offs must be considered when choosing the type of model that will be employed; such as, the length of time it takes for a user to learn the method, the quality of the underlying algorithm, flexibility of a range of data types and computational demands for example (Elith and Leathwick, 2009).

Table 3.1: Species Distribution Model Critique

Model Software Interface	Models within Software Interface	Statistical Category	Distribution Data	Pros	Cons	Rejection or use: reason
R and associated R Studio	User defined modelling packages e.g. DISMO and mgcv Generalised Additive Model (GAM) Generalised Linear Model (GLM)	Regression	Presence/Absence	• Species Distribution packages available (e.g. DISMO) • Extensive Model evaluation can be performed	• An experienced R User required or detailed instructions on R script required. • Time consuming trying to find and/or write script • Not a great user interface. • Other R user interfaces such as R studio or Brodgar no more helpful	**Rejected**: Too complicated and time consuming to learn how to use. Specific training courses would be required. No suitable Presence/Absence data.
Biomapper	Ecological niche and habitat suitability	Factor Analysis	Presence	• none	• Too many separate downloads • Had to use separate programmes to convert data etc.	**Rejected:** Too many technical issues to warrant proceeding any further with this model.

Table 3.1 (continued): Species Distribution Model Critique

Model Software Interface	**Models within Software Interface**	**Statistical Category**	**Distribution Data**	**Pros**	**Cons**	**Rejection or use: reason**
Modeco				• Good choice of model types • Many options for model evaluation	• Need a good understanding about the models to ensure that the evaluation is set appropriately. • Technical issues meant software repeatedly crashed and continually lost data	**Rejected:** Too many technical issues to warrant proceeding any further with this model interface.
Desktop Garp	GARP	Genetic Algorithm	Presence	• none	• Downloaded interface never worked.	**Rejected:** Too many technical issues to warrant proceeding any further with this model.

Table 3.1 (continued): Species Distribution Model Critique

Model Software Interface	**Models within Software Interface**	**Statistical Category**	**Distribution Data**	**Pros**	**Cons**	**Rejection or use: reason**
ESRI ArcMap	Environmental Envelope Analysis (EEA)	User defined Envelope Analysis	Presence	• Once user is capable of defining a modelling method and creating models, the software provides a good basis for EEA. • No need to learn a separate software method or import results for conversion in ArcMap.	• A relatively good understanding of ArcMap is required • Reliance on some software add ons • Fairly time consuming setting up and investigating various methods.	**<u>Selected</u>: A number of EEA methods were tested and a new method for the selection of the envelope was developed (See Chapter 4). The method was used to check and validate the Maxent model.**
		User defined model add ons	Presence and Presence/Absence	If experienced, models such as Maxent can be added in	• An advanced understanding of ArcMAP model building and script preparation is required to build models.	**Rejected:** more time consuming to learn how to integrate model to software than using the model interface itself.

Table 3.1 (continued): Species Distribution Model Critique

Model Software Interface	**Models within Software Interface**	**Statistical Category**	**Distribution Data**	**Pros**	**Cons**	**Rejection or use: reason**
Diva-GIS	Bioclim	Environmental Envelopes	Presence	• Diva-GIS was fairly easy to understand once the layers are prepared. • Software contains a good selection of statistical and other tools complementary to the model run	• Setting up of the environmental layers/grids was slightly more time consuming than using some of the other interfaces. • The output maps were more simplistic than those presented within other models	**Selected/Rejected:** This model was identified as a good model and interface to use, once issues with layer preparations were solved. However, once modelling outputs were compared, the interface was rejected based on the quality of the output compared to Maxent
	Domain	Similarity	Presence			

Table 3.1 (continued): Species Distribution Model Critique

Model Software Interface	**Models within Software Interface**	**Statistical Category**	**Distribution Data**	**Pros**	**Cons**	**Rejection or use: reason**
Maxent	Maxent	Maximum Entropy	Presence	• Relatively straight forward method to learn • Good literature available on methods for preparation of environmental layers, even for novice users. • Ease of importing results into ArcMap • Ability to easily use model interface to project future scenarios from the baseline. • Visual outputs are easily interpreted. • Ability to specify pseudo-absence bias and criteria	• A good understanding of GIS software is useful for preparation of new environmental layers. • Not really possible to carry out sensitivity testing to the algorithm itself within this interface.	**<u>Selected</u>: This was by far the easiest model interface to learn and use. Once variable layers had been prepared, running and evaluating the model was simple and straight forward and the outputs had enough level of complexity to provide good results. Projections provide good illustration of future scenarios.**

Table 3.1 (continued): Species Distribution Model Critique

Model Software Interface	**Models within Software Interface**	**Statistical Category**	**Distribution Data**	**Pros**	**Cons**	**Rejection or use: reason**
OpenModeller	Aquamaps			• Wide variety of models available within one interface • Models can be run simultaneously and compared. • Can connect directly to online species databases. Therefore limits need for separate species data search.	• Fairly laborious interface to use • Time consuming to prepare all layers required and not very intuitive as to where files are saved • Many technical issues experienced • Interface repeatedly crashed and data lost • The online database connection only provides individual specimen records and is therefore not applicable to this study	**Rejected**: Initially liked the user interface, but too time consuming preparing layers and technical issues meant data was lost when used.
	Artificial Neural Network	Machine Learning/ Regression	Presence (plus pseudo-absences) and Presence/Absence			
	Bioclim	Envelope	Presence			
	Climate Space Model					
	ENFA (Ecological Niche Factor Analysis)	Factor Analysis	Presence			
	Envelope Score					
	Environmental Distance					
	GARP (Genetic Alogrithm for Ruleset Production)	Genetic Algorithm	Presence			

Table 3.1 (continued): Species Distribution Model Critique

Model Software Interface	**Models within Software Interface**	**Statistical Category**	**Distribution Data**	**Pros**	**Cons**	**Rejection or use: reason**
OpenModeller (cont.)	Maximum Entropy	Maximum Entropy/ Regression	Presence	As above	As above	As above
	Niche Mosaic					
	SVM (Support Vector Machines)	Machine learning/ Kernel	Presence (plus pseudo-absences)			

3.3.2 Selected Models

Maxent

Maximum entropy, Maxent (Phillips *et al.*, 2006) is a predictive method that is used to model the geographic distribution of species using presence-only data through the determination of the species environmental requirements and bases the overall prediction on maximum entropy (Phillips *et al.*, 2006; Phillips and Dubik, 2008; Jones *et al.*, 2012), through a machine-learning niche based model . Maxent has been used in a number of comparative studies examining the effectiveness of species distribution modelling (SDM) in the marine environment (Jones *et al.*, 2012; Reiss *et al.*, 2011; Ready *et al.*, 2010) and is considered to be reliable in this context (Reiss *et al.*, 2011).

Maxent is regarded as a strong performer when compared to other modelling methods such as BIOCLIM, GARP and ENFA, which has ultimately led to its popularity and use in conservation management modelling; along with its ease of use; and why it was selected for use within this study.

Maxent uses exponential distribution, and its unbound probabilities can lead to high predictions for variables outside the study range (Phillips *et al.*, 2006). The potential for over prediction of distribution when studying individual species has been acknowledged by Ross and Howell (2012). They suggested that it would therefore be potentially more suitable to apply the use of predictive modelling to a habitat formed by a species, rather than to the indicator species itself. This principle has been taken into consideration within this study.

Model validation and results are addressed in Chapter 4; Section 4.2.5.

Limitations, Uncertainties and Caveats of Species Distribution Models

It is acknowledged that a number of limitations and uncertainties exist with SDMs and the use of uncertain predictive maps may lead to inefficient decision-making; therefore it is important to acknowledge these uncertainties and quantify them where possible to aid better SDM outputs (Vierod *et al.*, 2014).

Vierod *et al.* (2014) summarise these issues in relation to deep-sea SDMs; however the issues are still relevant to other marine ecosystems. They categorise the issues as follows:

- process errors;
- observation errors;
- sample selection bias and presence-only models;
- spatial autocorrelation;
- issues of scale;
- model evaluation; and
- validation

A number of other studies outline the limitations and "pitfalls" of SDMs with regard to areas of further study (Araújo and Guisan, 2006); the lessons learned from terrestrial modelling when applied to the marine environment (Robinson *et al.*, 2011); sample size (Wisz *et al.*, 2008); the uncertainties of absence records (Lobo *et al.*, 2010); and the pitfalls associated with their use in conservation and/or climate change planning (Loiselle *et al.*, 2003; Sinclair *et al.*, 2010). From a conservation planning point of view, it is also important to consider that SDMs do not take into account a number of biological factors, including: species mobility, evolution and adaption, capacity to emigrate (Sinclair *et al.*, 2010), anthropogenic pressures and larval dispersal (e.g. process errors).

A number of these limitations have been considered within this thesis. The use of Maxent was not only based on ease of use; and it is highlighted that this thesis by no means advocates the use of modelling without due consideration of said limitations and caveats; but is also based on its suitability of the environment within which the studies were based i.e. marine.

The studies within this thesis considered the limitations outlined by Vierod *et al*. (2014). Maxent is sometimes considered and at times criticised as a "black box" for SDM (Halvorsen, 2013), and that people utilising the model do not give due consideration to the statistical validation methods running behind it – and whether they are most suitable for the purpose, environment or species being modelled.

With regard to model evaluation, it is acknowledged that a number of methods are available. These studies presented herein rely on the internal 'Area under the Curve' (AUC) function within Maxent. However, it should be stated that limitations are apparent with this methodology given that the AUC was primarily developed for presence-absence models (Lobo *et al.*, 2010; Vierod *et al.*, 2014). Use of the AUC with presence/pseudo-absence data can be problematic as the background points do not contain information about the species occurrence. As a result, the AUC value is reduced when a wider species niche is observed (Vierod *et al*., 2014).

Although these limitations have been considered, there are still uncertainties with regard to the suitability of SDMs within the planning realm and arguments for and against their use will always be present. Caveats are therefore placed on all the studies carried out in this thesis (primarily Chapters 4 and 5). Although, best practice has been undertaken with regard to the modelling methods employed herein, all results should be treated with caution. The results provide suggested evidence for consideration within marine conservation planning, but by no means should be used solely for this purpose.

Environmental Envelope Analysis

The environmental envelope of a species is defined as the set of environments within which it is believed that the species can persist: that is where its environmental requirements can be satisfied (Walker and Cocks, 1991).

User defined Environmental Envelope Analysis (EEA) methods vary greatly depending on the chosen "envelope" criteria. In this particular study, a new method, as far as the author is aware, for defining the environmental envelope for *M. modiolus* beds has been developed. Full details of this method are discussed in Chapter 4.

Environmental Envelope Analysis Method Testing

Two other proposed methods were also investigated (Jarnevich *et al.*, 2007; Powell *et al.*, 2005), but these methods were judged to be unsuitable for the data used within this particular study, as described below.

The method proposed by Jarnevich *et al*. (2007) describes the development of an EEA method as a rapid assessment technique to estimate the potential distribution of a species given its present location and associated environmental attributes. Their method noted the minimum and maximum of each independent variable within ArcMap for all locations that the particular target species is present (Jarnevich *et al.*, 2007). These minimum and maximum values together create the environmental envelope. The output of the model informs how many of the input variables lie within the environmental envelope of the species (Jarnevich *et al.*, 2007).

The results of this EEA method for *M. modiolus* beds are shown in Table 3.2 and Figure 3.10. The problem with this method and the reason for rejection is based on the realisation that the envelope is too large. This method, although correct in its assumptions (that a species can occur anywhere within the minimum and maximum range of normal distribution), is simply not selective enough. The probability that the species will always occur at its minimum and maximum range is reduced based on statistical relevance. This is an issue that is addressed within our method.

Powell *et al.* (2005) used a method of EEA which appeared to be based on descriptive qualities of the environmental attributes at the given location of each of their individual populations. This method was applied to the *M. modiolus* bed population data. Problems with this method were encountered almost immediately based on the number of *M. modiolus* bed populations compared to the limited number of populations used within their study. Powell *et al.* (2005) then grouped their populations based on the attributes and assigned to a "Habitat Category"; resulting in 3 potential habitat categories or envelopes.

Each *M. modiolus* bed population was identified and the description of the envelope for each environmental attribute was noted. The results of which are shown in Table 3.3. As Table 3.3 shows, the variability of the population envelopes made it impossible to group the populations into habitat categories. Results using this method essentially showed that each *M. modiolus* bed had its own habitat category. It was not possible to map the envelope created with this method.

All EEA methods were based on "population", rather than the individual bed locations. "Population" in this context is defined as grouping of the bed occurrence records based on location and proximity to each other. Populations were selected if the occurrence records were within 10km of each other, excluding areas of obvious boundaries, e.g. land or sealochs etc. Within this 10km population grouping, the individual occurrence records were given a 1km buffer which would represent bed extent within that particular population.

Table 3.2: *Modiolus modiolus* environmental envelope following Jarnevich *et al.* (2007) method

	Envelope
Bathymetry	0 to -250m
Slope	0 to 2.95%
Temperature	7 to 10 °C
Current Speed	0.02 to 1.7 m/s
Salinity	25 to 35 ppt
Landscape	shelf coarse sediment plain - weak tide stress
	Shelf mixed sediment plain - weak tide stress
	Shallow coarse sediment plain - moderate tide stress
	Shelf coarse sediment plain - moderate tide stress
	Shallow sand plain
	Shallow coarse sediment plain - weak tide stress
	Aphotic rock
	Shelf mound or pinnacle
	Photic rock
	Shallow mixed sediment plain - weak tide stress
	shallow coarse sediment plain - strong tide stress
	Bay
	Shallow mud plain
	Shelf coarse sediment plain - strong tide stress
	Estuary
	Shelf mixed sediment plain - moderate tide stress
	Shallow mixed sediment plain - moderate tide stress
	Embayment
	Shelf trough
	Sealoch

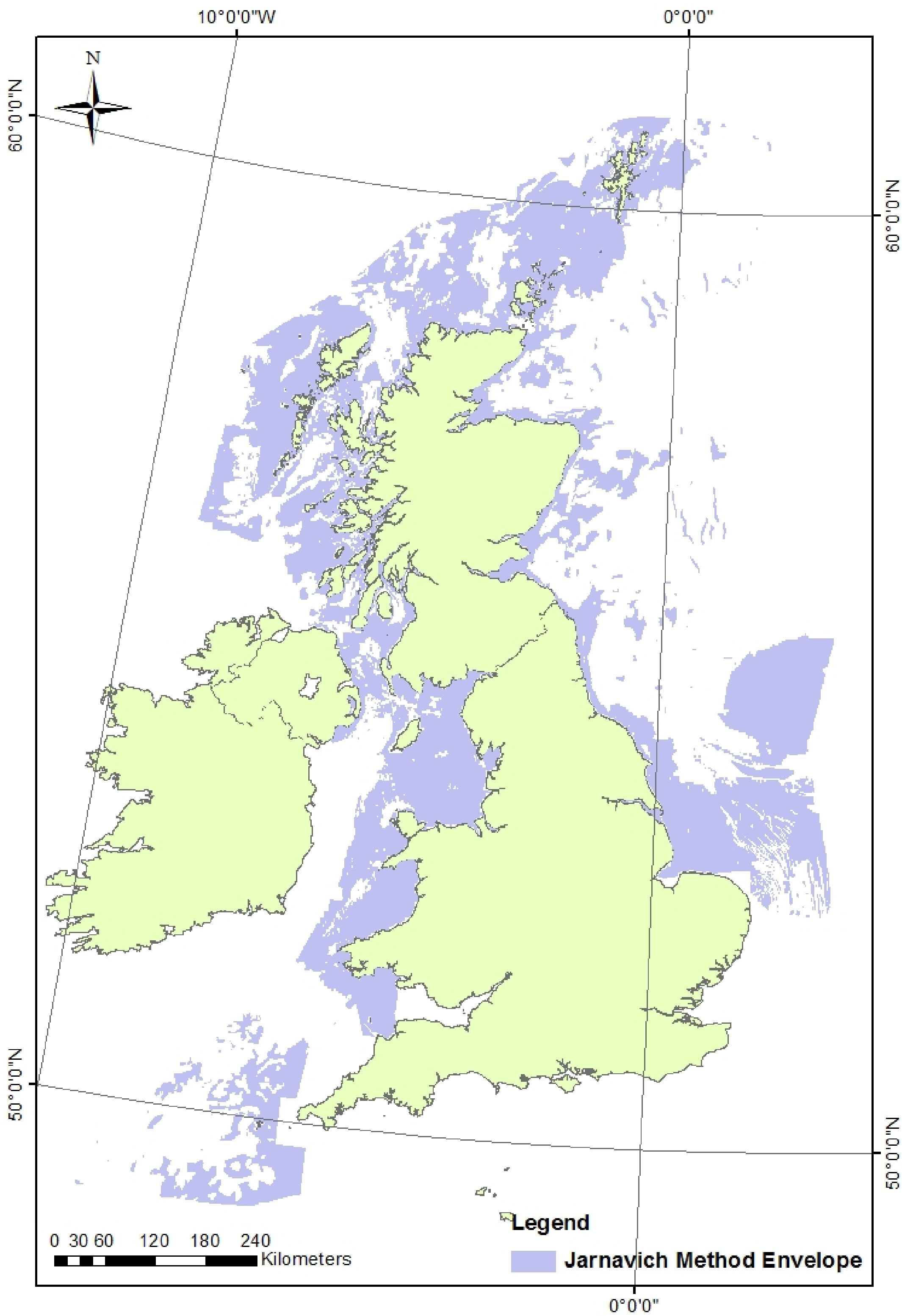


Figure 3.10: ***Modiolus modiolus*** **environmental envelope following Jarnevich *et al.* (2007) method**

Table 3.3: *Modiolus modiolus* environmental envelope following Powell *et al.* (2005) method

Population	Depth	Slope	Current Speed	Temperature	Salinity	Landscape			
East of England									
Flamborough	20 to 40	<1	1.0 – 1.5	7	34	Shelf mixed sediment plain – moderate tide stress	Shallow mixed sediment plain – moderate tide stress		
Scarborough	50	<1	0.5 – 1.0	8-9	34	Shelf coarse sediment plain – weak tide stress	Shelf mixed sediment plain – weak tide stress		
East Scotland									
Caithness	10 to 50	<1	0.5 – 1.5	9	35	Shallow corase sediment plain – moderate tide stress	Shallow Corase Sediment Plain – Weak tide stress		
Moray Firth	0 to 5	<1	0.0 – 0.5	9	35	Shallow Sand Plain	Bay	Estuary	
Hebrides									
East Lewis	0 to 5	<1	0.0 – 1.0	10	34	Sealoch			
West Lewis	0	<1	0.5 – 1.0	9	34-35	Sealoch			

Table 3.3 (continued): *Modiolus modiolus* environmental envelope following Powell *et al.* (2005) method

Population	Depth	Slope	Current Speed	Temperature	Salinity	Landscape			
Irish Sea									
North Lleyn	0 to 40	<1	0.5 – 1.5	6-10	34	Shallow corse sediment plain – moderate tide stress	Shallow Sand Plain	Shallow Corase Sediment Plain – Weak tide stress	
Anglesey	50	<1	1 – 1.5	10	34	Shallow corse sediment plain – moderate tide stress	Shelf coarse sediment plain – moderate tide stress		
Irish Sea	50 to 250	<3	1.0 – 2.0	10	34	Shelf coarse sediment plain – moderate tide stress	Shelf mound or pinnacle	Shelf coarse sediment plain – strong tide stress	Shelf Trough
Strangford	0 to 5	<1	0.5 – 1.0	9	34	Shallow mixed sediment plain – weak tide stress	Shallow mud plain	Sealoch	
Ards	0 to 30	<1	0.0 – 1.0	9	34	Shallow Corase Sediment Plain – Weak tide stress	Shallow mixed sediment plain – weak tide stress		
South Isle of Man	10 to 50	<1	1.0 – 2.0	10	34	Shallow corase sediment plain – moderate tide stress	Shelf coarse sediment plain – moderate tide stress	Shallow Corase Sediment Plain – strong tide stress	
North Isle Man	10 to 20	<1	1.0 – 1.5	10	33-34	Shallow corase sediment plain – moderate tide stress	Shallow Sand Plain		

Table 3.3 (continued): *Modiolus modiolus* environmental envelope following Powell *et al.* (2005) method

Population	Depth	Slope	Current Speed	Temperature	Salinity	Landscape			
Orkney									
Cava	0 to 5	<1	0.0 – 1.0	8-9	35	Embayment			
Copinsay	0 to 75	<1	0.5 – 1.0	9	35	Shallow Corase Sediment Plain – Weak tide stress	Aphtoic rock	Sealoch	
Sanday	5 to 40	<1	0.5 – 1.5	9	35	Shallow Corase Sediment Plain – Weak tide stress	Photic rock		
Shapinsay	0 to 20	<1	0.0 – 1.5	9	35	Shallow Corase Sediment Plain – Weak tide stress	Photic rock	Shallow mixed sediment plain – weak tide stress	

Table 3.3 (continued): *Modiolus modiolus* environmental envelope following Powell *et al.* (2005) method

Population	Depth	Slope	Current Speed	Temperature	Salinity	Landscape			
Shetland									
East Mainland Shetland	0 to 50	<1	0.0 – 1.0	10	34-35	Shallow Corase Sediment Plain – Weak tide stress	Sealoch		
Heylor	0	<1	0.5 – 1.0	9	34-35	Sealoch			
Kettla Ness	0 to 5	<3	0.0 – 1.0	9	35	Shallow Sand Plain	Shallow Corase Sediment Plain – Weak tide stress		
Linga	0 to 10	<1	0.0 – 1.0	8	34-35	Shallow Sand Plain	Sealoch		
North Mainland Shetland	0 to 5	<1	0.0 – 2.0	9	34-35	Shallow Sand Plain	Shallow Corase Sediment Plain – Weak tide stress	Shallow mixed sediment plain – weak tide stress	Sealoch
Shelberry	5	<1	0.5 – 1.0	8	34-35	Photic rock	Sealoch		
South Mainland Shetland	0 to 20	<1	0.0 – 1.0	9	34-35	Shallow Sand Plain	Shallow mixed sediment plain – weak tide stress	Shallow mud plain	Sealoch
Sullom Voe	0 to 5	<1	0.5 -1.0	9	34-35	Sealoch			
West Mainland Shetland	0 to 5	<1	0.5 – 1.0	9	34-35	Shallow Sand Plain	Shallow mixed sediment plain – weak tide stress	Sealoch	
Yell	0 to 5	<1	0.0 – 1.0	9	34-35	Sealoch			

Table 3.3 (continued): *Modiolus modiolus* environmental envelope following Powell *et al.* (2005) method

Population	Depth	Slope	Current Speed	Temperature	Salinity	Landscape			
West Scotland									
Isle of Skye	0 to 5	<1	0.0 - 1.0	9	34	Shallow Sand Plain	Shallow Corase Sediment Plain - Weak tide stress	Sealoch	
Loch Broom	0	<1	0.5 - 1.0	9	34	Sealoch			
Loch Carron	0 to 5	<1	0.5 - 1.0	9	34	Sealoch			
Loch Craignish	0	<1	0.0 - 1.0	10	33-34	Sealoch			
Loch Creran	0 to 5	<1	0.5 - 1.0	10	34	Sealoch			
Loch Duich	0	<1	0.5 - 1.0	9-10	34	Sealoch			
Loch Ewe	0 to 5	<1	0.5 - 1.0	9	34	Sealoch			
Loch Fyne	0 to 5	<1	0.5 - 1.0	10	33-34	Sealoch			
Loch Glean Dubh	0	<1	0.5 - 1.0	9	34	Sealoch			
Loch Laxford	0	<1	0.5 - 1.0	9	34-35	Sealoch			
Loch Leven	0	<1	0.5 - 1.0	10	34	Sealoch			
Loch Sunart	0 to 5	<1	0.0 - 1.0	9-10	34	Sealoch			
Loch Sween	0 to 5	<1	0.5 - 1.0	9	34	Sealoch			
Upper Loch Linnhe	0 to 5	<1	0.0 - 1.0	10	34	Sealoch			

3.3.3 Environmental Parameters

A requirement for species distribution models is a set of environmental parameters on which to base the "environmental niche/envelope" predictions. The quality and ultimately the availability of certain environmental parameters will impact on the overall output from a model. Quality of data may be assessed in terms of its geographic coverage, resolution and whether the data are modelled or ground truthed (e.g. actual surveyed data). Environmental parameter selection should be based on identified criteria for the selected species e.g. the factors that influence the species distribution. In relation to the selected models the parameters that were considered to be most important to *M. modiolus* beds are discussed in more detail in Chapters 2; Section 2.3.1 and 4; Section 4.2.2.

A number of potential environmental parameters were identified from available online sources for inclusion in the selected modelling methods as outlined in Table 3.4.

Table 3.4: Available Environmental Parameter Data

Environmental Parameters	**Description**	**Data Source**	**Resolution**
Seabed Habitats	EUNIS 2007-11 classification system	UKSeaMap 2010: http://jncc.defra.gov.uk/page-5534	0.0025 decimal degrees
Geology		Marine Digimap: university licence	Unknown
Landscape	seabed and coastal marine landscapes were derived by integrating a number of geophysical attributes including bathymetry, seabed sediments, bedforms, maximum near-bed stress and other data, whilst the water column marine landscapes were based on two 'model derived', raster datasets for salinity and stratification	Mapping European Seabed Habitat (MESH): http://www.searchmesh.net/default.aspx?page=1974	Unknown
Substrate	The original UKSeaMap project and the MESH project used the following substrate classification to reflect the broad substrate types used in seabed habitat classifications: Rock, Coarse sediment, Mixed sediment, Sand and muddy sand and Mud and sandy mud	UKSeaMap 2010: http://jncc.defra.gov.uk/page-5534 (Connor *et al.*, 2006) (Davies and Moss, 2004) (Connor *et al.*, 2004)	Unknown
Sea Surface Temperature	Annual average climatological mean (^{o}C)	NOAA World Ocean Atlas: http://www.nodc.noaa.gov/cgi-bin/OC5/SELECT/woaselect.pl?parameter=1	0.25^{o}

Table 3.4 (continued): Available Environmental Parameter Data

Environmental Parameters	Description	Data Source	Resolution
Sea Bottom Temperature	Annual average climatological mean (°C)	NOAA World Ocean Atlas: http://www.nodc.noaa.gov/cgi-bin/OC5/SELECT/woaselect.pl?parameter=1	0.25°
Surface Salinity	Annual average climatological mean	NOAA World Ocean Atlas: http://www.nodc.noaa.gov/cgi-bin/OC5/SELECT/woaselect.pl?parameter=2	0.25°
Bottom Salinity	Annual average climatological mean	NOAA World Ocean Atlas: http://www.nodc.noaa.gov/cgi-bin/OC5/SELECT/woaselect.pl?parameter=2	0.25°
Primary Production	Mean ($mgC \cdot m^{-2} \cdot day^{-1}$)	Aquamaps: http://www.aquamaps.org/	0.5°
Depth	The GEBCO_08 Grid: largely generated by combining quality-controlled ship depth soundings with interpolation between sounding points guided by satellite-derived gravity data (m)	General Bathymetric Charts of the Ocean (Gebco): http://www.gebco.net/data_and_products/gridded_bathymetry_data/	30-Arc Second
Current Speed	average spring current speed (ms-1)	Marine Renewables Atlas: http://www.renewables-atlas.info/ Supplemented by: Current speed data on UKHO Navigation Charts (Marine Digimap, 2012) and BODC oceanographic data (BODC, 1998)	1/60° Latitude; 1/40° Longitude and 1.8km horizontal
Euphotic Depth	The euphotic depth: depth at which light intensity falls to 1% of the value at the surface of a body of water. It refers to the "lighted zone" of the water column in which photosynthesis can take place. Euphotic depth is influenced by phytoplankton, coloured dissolved organic matter, and suspended particulate matter. (m)	NASA Giovanni portal: http://disc.sci.gsfc.nasa.gov/giovanni	4km

3.3.4 Data Processing

In order to use the environmental parameters in the identified models, it was essential to format the data in a GIS programme (ESRI ArcMap versions 9.3 and 10.1). Figure 3.11 illustrates the steps involved in the data conversion process.

The data were downloaded from the source websites in different formats, therefore all data needed to be converted into the same format. The required formats included: Vector format for use in the Environmental Envelope Analysis; and Raster/ASCII format for use in the Maxent model. All data sources were also required to be projected into the same co-ordinate system. The co-ordinate systems used within the study were either Geographic Co-ordinate System (GCS) WGS 1984 or Projected Co-ordinate System (PCS) WGS 1984 UTM Zone 31N.

The data were required to be the same extent as each other and therefore were clipped to the smallest layer. If necessary, environmental layers were altered slightly to provide more detail along the coast.

A model was created in ArcGIS 9.3 (Figure 3.12) which projected, clipped and converted the created rasters into the same format for running in the external models. This process was employed instead of using an intersect tool within GIS as described by Marshall (2011) as there was more control of the specific output requirements. Within this model, the raster extraction environments were set to extract all layers by a mask to ensure an equal extent.

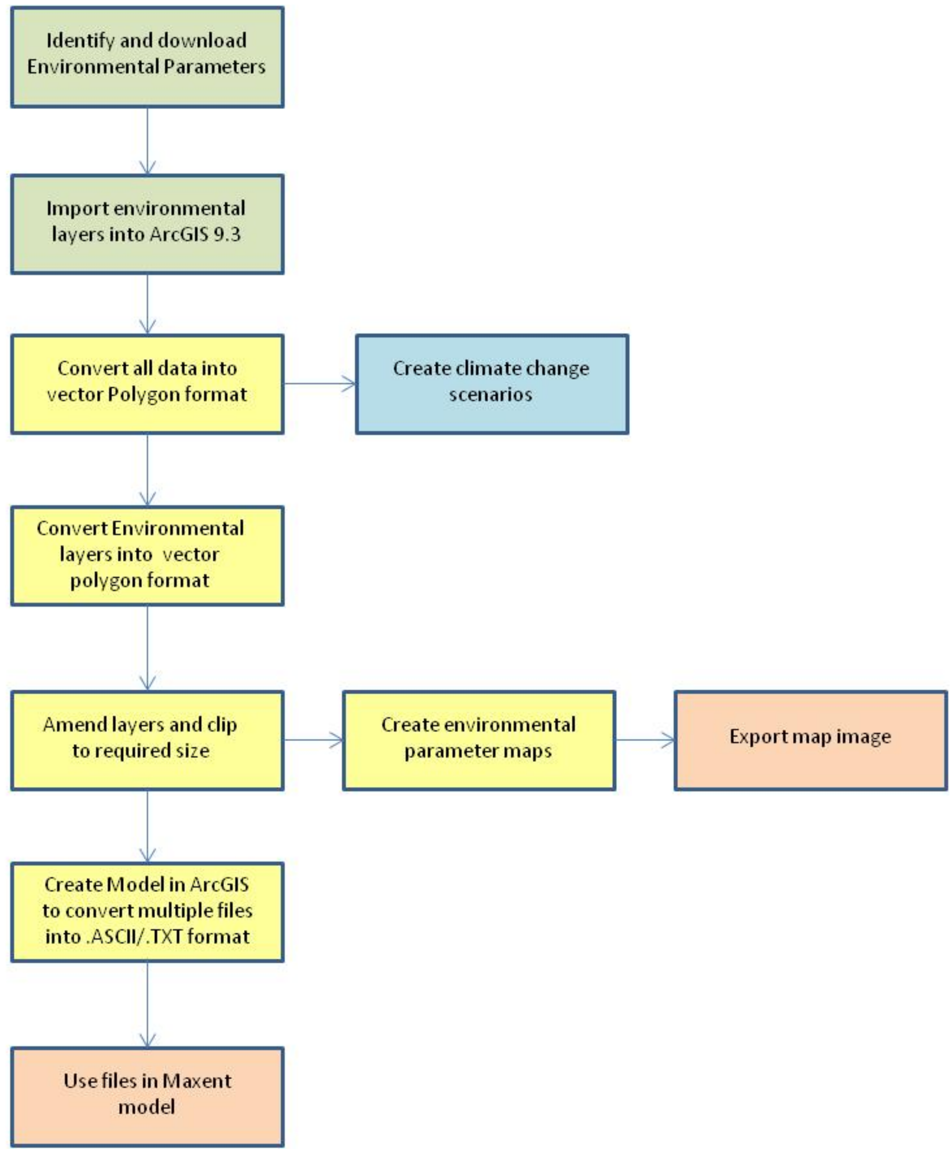


Figure 3.11: Flowchart illustrating the steps involved in the data formatting process.

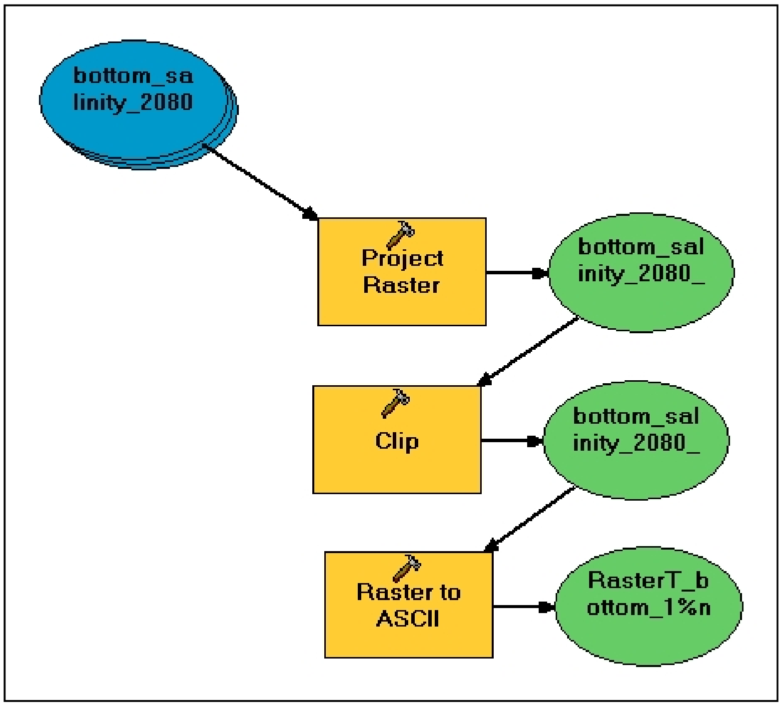


Figure 3.12: Model created in ArcGIS 9.3 to convert multiple Raster files into ASC files in the same format and projection

3.3.5 Increased Temperature Scenarios

Increased temperature scenarios were required for use in the models to predict potential change to the species distribution. No existing climate change scenario data were available for the marine environment that were easily useable and interpreted. It was therefore necessary to create the scenarios from baseline environmental parameters as outlined in the above section (Table 3.4).

The NOAA sea temperature data proved to be the most functional in terms of suitability for adaption to scenarios, overall spatial cover, usability, ease of data preparation and formatting, ease of understanding data and the provision of temperature by depth, compared to sea temperature data held by for example the WorldClim Database (Hijmans *et al.*, 2005), the Hadley Centre (Jones and Salmon, 2011) and the Earth Observatory, NASA (NASA, 2012).

The annual climatology data were downloaded from the NOAA WOAselect website (NOAA, 2009) to a grid resolution of 0.25^{o} in ArcGIS shapefile format. The downloaded shapefile was imported into ArcGIS 9.3. The data were only available in point format, therefore needed to be converted into a polygon format before the creation of climate change scenarios.

The point data were clipped to an area encompassing the UK waters and converted to Raster format prior to conversion to polygon format. The edges of the polygon were adjusted to incorporate areas that had no temperature data. An average temperature in the neighbouring polygons was used to establish a temperature for these areas.

Creating the Scenarios

From the original point data attribute table the data available included surface and depth temperature from 10m to potentially 5500m below the surface. The original point data were assigned co-ordinates and the surface data and depth data down to the greatest depth for the study area (in this instance 200m) was exported to an excel spreadsheet. Once in the spreadsheet, the data were formatted to include only surface and bottom temperature.

In order to create the climate change scenarios, it was necessary to identify the timescale. It was decided that the scenarios would run up to 2100 as this is the figure most widely quoted in the climate change literature (IPCC, 2007). Suitable interval years of 2030, 2050 and 2080 were also chosen based on the general outline of scenario planning (IPCC, 2007) and it was necessary to have only a few interval years that were not too close together in order to see any potential changes.

The UK09 Project (Marine Scotland, 2011) used the IPCC climate change scenario A1B for an indication of climate change, which stated that there would be a 4^{o}C increase in sea surface temperature by 2100. Therefore the temperature increase for the interval years was calculated as follows:

Temperature increase = (pYr-bYr)*(maxT/maxYr)

Where: bYr = base year (2009), pYr = prediction year (2030, 2050, 2080, 2100), maxT = maximum temperature increase (4^{o}C), maxYr = number of years from base year to maximum predicted year (91)

The temperature increases are presented in Table 3.5.

It was decided to apply these temperature increases to the bottom temperature too as no literature was available to suggest how sea surface temperature increase may impact on temperature at depth. It may be the case that the temperature increase is negligible as ocean depths may be less affected by changes in temperature, or temperature increases (or decreases) may be greater as it may be impacted by changes in water circulation and melting ice caps for example. However, in order to find a compromise, and to keep the data formatting simpler, the same figure was used.

The temperature increases were applied to the surface and bottom temperatures in the Excel spreadsheet and the overall average temperature for each year and depth was calculated (Figure 3.13).

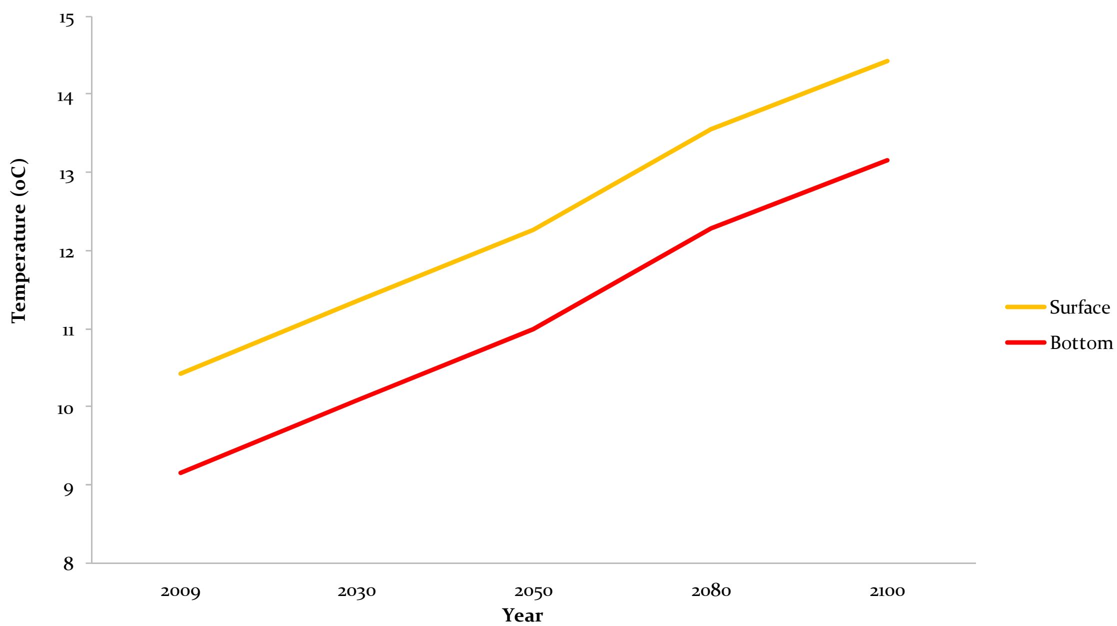


Figure 3.13: Predicted temperature increases at the ocean surface and bottom based on UKCP09 Project ocean temperature predictions under IPCC SRES A1B (4^{o}C increase by 2100)

Applied to 2009 average climatic annual mean ocean temperature - Averaged for waters surrounding UK only.

The figure illustrates increase in temperature calculated for this study and is not based on actual IPCC temperature predictions. Temperatures were calculated based on the assumption that there will be a uniform increase over depth per year, which will not necessarily reflect the actual situation.

The calculated scenarios were imported into ArcGIS and were formatted from point to polygon shapefiles as described above.

In addition to creating temperature scenarios, it was important to investigate whether other parameters that were to be used in the models would change as a result of climate change. It is understood that sea level rise is also an important factor of climate change with a reported rise of 0.59m between 2007 and 2107 (IPCC, 2007). Therefore it was decided to calculate the difference in the same way as was carried out for the temperature, the results are presented in Table 3.5.

These differences in depth were applied to the depth data (following conversion of depth data to point format and export to excel). Depth data obtained for this study were not at a high enough resolution to incorporate such a small change (i.e. the data were whole numbers), therefore a projected scenario could not be established for depth, given the data used.

It was also decided that salinity should be included in these scenarios too. However, the literature on the change in salinity due to climate is practically non-existent and is limited to a few discussion type articles which have conflicting opinions (Adam, 2008; IPCC, 2007). IPCC (2007) reports a potential for a decrease in salinity, although no suggested figures were included. It was decided to go with the IPCC view of a decrease in salinity and an assumption was made that there would be a decrease of 1‰ between 2009 and 2100. These changes were applied to the NOAA surface and bottom salinity (calculated using the same method as for temperature) (NOAA, 2009). The change in salinity of the oceans may not be of great significance, and may be more of an issue to wetlands and saltmarshes etc, where increased temperatures may lead to increased evaporation and overall salinity, on a much greater extent.

Table 3.5: Temperature and Depth projected increases under IPCC scenario A1B

Year	Temperature (^oC)	Depth (m)
2009	0.000	0.012
2030	0.924	0.136
2050	1.844	0.254
2080	3.125	0.431
2100	4.000	0.549

Source: Adapted from (IPCC, 2007)

3.3.6 Conclusions

Following review of all available data sources it was concluded that in general a good array of suitable environmental data are available for use publically and freely. However, as would be expected with free data, some datasets, e.g. depth, the resolution was not as fine as may be found in purchased datasets.

In addition, the array of modelling interface software available freely was surprising; however, the usability of these interfaces was slightly disappointing. Unfortunately it was assessed that only two interfaces (Maxent and EEA) out of nine (one of which was solely developed for the purposes of this thesis) provided a suitable modelling approach. In addition, the Maxent model selected has also been widely used and published (see Chapters 4 and 5 for details) – allowing for a suitable level of confidence in the results, especially within the marine environment.

The Maxent and EEA Species Distribution Modelling methods and data introduced in this Chapter are implemented and discussed in full in Chapters 4 and 5.

Chapter 4. Predictive Habitat Modelling of *Modiolus modiolus* Beds

4.1 Introduction

It is widely accepted that the natural distribution patterns of organisms are primarily driven by their environmental requirements (Pearson *et al.*, 2002); and that climate change is potentially having an impact on natural distribution patterns through range expansion, contraction and migration (Pearson and Dawson, 2003; Thomas *et al.*, 2012). The effect climate change has on geographic distribution is often assessed in terms of potential envelopes/spatial niches shifting in altitude, longitude or latitude; and this influence could in turn, threaten biodiversity and the conservation of many species (del Barrio *et al.*, 2006; Thomas *et al.*, 2012; Thuiller, 2003).

Data on the distribution of marine species and habitats are often limited, mainly because of the complexity and costs of surveying and sampling extensive sea areas. For example, habitat maps based on survey data and ground truthing[5] currently cover just 10% of the UK continental shelf (Aish *et al.*, 2010). The use of predictive species distribution modelling might therefore provide a suitable tool to fill knowledge gaps but, it may be subject to the issue of over-prediction of range when studying individual species (Ross and Howell, 2012). Ross and Howell (2012) acknowledged that a more robust approach might be to apply predictive modelling methods to a habitat formed by a species, rather than to the indicator species itself. This principle has been adopted in the present study.

[5] Ground truthing: the collection of data in the field to test the accuracy or otherwise of a scientific model

4.1.1 Aims and Objectives

- ***Research Overview:*** *This chapter will utilise the methods identified in Chapter 3 to determine what effect an increased ocean temperature will have on the distribution of Modiolus modiolus beds around the UK. This will contribute to the research by identifying what issues may be faced from a policy point of view, if a species of conservation importance is lost and to provide a new tool to inform the MSFD spatial management process for key habitats*

  Key Tasks:
  - *Investigate what the environmental limits/envelope of the feature are*
  - *Investigate if the distribution of the feature change due to climate change*
  - *Investigate what the impacts or management requirements are if the feature is lost*

The objective of this study is to explore the use of a predictive Species Distribution Model (SDM) and a Geographical Information System (GIS) based Environmental Envelope Analysis (EEA) method to create modelled habitat maps for a priority habitat: the biogenic horse mussel reefs formed by the bivalve mollusc *Modiolus modiolus* (Linnaeus, 1758).

Although *M. modiolus* is a widespread and common species, actual horse mussel beds are limited in their distribution (Elsäßer *et al.*, 2013) and often represent biodiversity 'hotspots' (e.g. Rees *et al.*, 2008), some of which have been, or are in the process of being selected for Marine Protected Areas (Lindenbaum *et al.*, 2008; Hirst *et al.*, 2012b; Hirst *et al.*, 2012a). Dense aggregations/beds reach their southerly limit around the British Isles, in the Irish Sea. This suggests that their occurrence around the British Isles may be vulnerable to a long-term rise in water temperature (Holt *et al.*, 1998; Brown, 1984).

M. modiolus beds are thought to play an important role in benthic productivity and seabed stabilisation. The beds contribute to high biodiversity and may provide refugia and feeding opportunities to other marine organisms (Elsäßer *et al.*, 2013; Ragnarsson and Burgos, 2012; Fariñas-Franco *et al.*, 2013). Although maps of bed distribution have been created, there is still a considerable amount of uncertainty as to the true extent of these beds within the OSPAR region (Rees, 2009c).

The primary goal of this study is to use publicly available datasets to test the modelling approaches for a *Modiolus* habitat case example, to see whether it may provide a new tool to inform the MSFD spatial management process for key habitats. The models will be applied to determine the extent of habitat suitable for *M. modiolus* beds under current baseline conditions; predict habitat loss under an increased ocean temperature scenario; and demonstrate the application of a predictive habitat mapping tool for "future-proofing" spatial planning for habitats and biodiversity management planning.

Limitations, uncertainties and caveats for the use of SDMs are outlined in Section 3.3.2.

4.2 Methods

4.2.1 Modiolus modiolus Presence Data

M. modiolus bed occurrence records were extracted from the 2011 OSPAR priority habitats dataset (JNCC, 2012a) and corrected based on areas of uncertainty published by Rees (Rees, 2009c). The data were supplemented with occurrence records collected during more recent UK surveys (Hirst *et al.*, 2012a; Hirst *et al.*, 2012b; Sanderson, unpubl.). A total of 215 occurrence records were obtained (Figure 4.1). As a result of the limited geographical coverage of some of the environmental layers, 82 records were excluded[6] because they did not coincide with the environmental layers.

4.2.2 Environmental Data

Data on environmental variables of potential biological relevance to *M. modiolus* were obtained from publically available sources (Table 4.1; see also Chapter 3) then assigned to a 0.005^{o} grid using ArcMap 9.3 Geographical Information System (GIS) software. Temperature, depth, substratum, water movement and salinity were chosen based on the *M. modiolus* environmental requirements as outlined by Holt *et al*. (1998), but water

[6]The Maxent model requires the presence data to coincide with the environmental layers in order to make predictions of the required environmental envelope. Data cannot be used if the layers do not overlap.

quality and suspended sediment were not available for inclusion in this model due to data resolution.

Table 4.1: Environmental variables and data sources

Variable	Source
Bathymetry: depth (m)	GEBCO_08 30-second arc Bathymetry resolution (GEBCO, 2011)
Slope: percentage gradient of the seafloor (%)	Adapted in ArcGIS 9.3 from: GEBCO_08 30-second arc Bathymetry resolution (GEBCO, 2011)
Sea Bottom Temperature: climatological annual mean sea bottom temperature (^{o}C). Adapted from NOAA depth interval data	NOAA World Ocean Atlas (Locarnini *et al.*, 2010)
Bottom Salinity: climatological annual mean sea bottom salinity (PSS). Adapted from NOAA depth interval data	NOAA World Ocean Atlas (Antonov *et al.*, 2010)
Landscape: seabed landscape features [Broad patterns in seabed character, such as seabed morphology determined by major geological and hydrographic processes]	UKSeaMap/MESH webGIS (Connor *et al.*, 2006) http://www.searchmesh.net/ ("Marine Landscapes" layer on interactive map)
Current Speed: average spring current speed (ms^{-1})	Atlas of UK marine renewable energy resources (DTI, 2004) Supplemented by: Current speed data on UKHO Navigation Charts (Marine Digimap, 2012) and BODC oceanographic data (BODC, 1998)

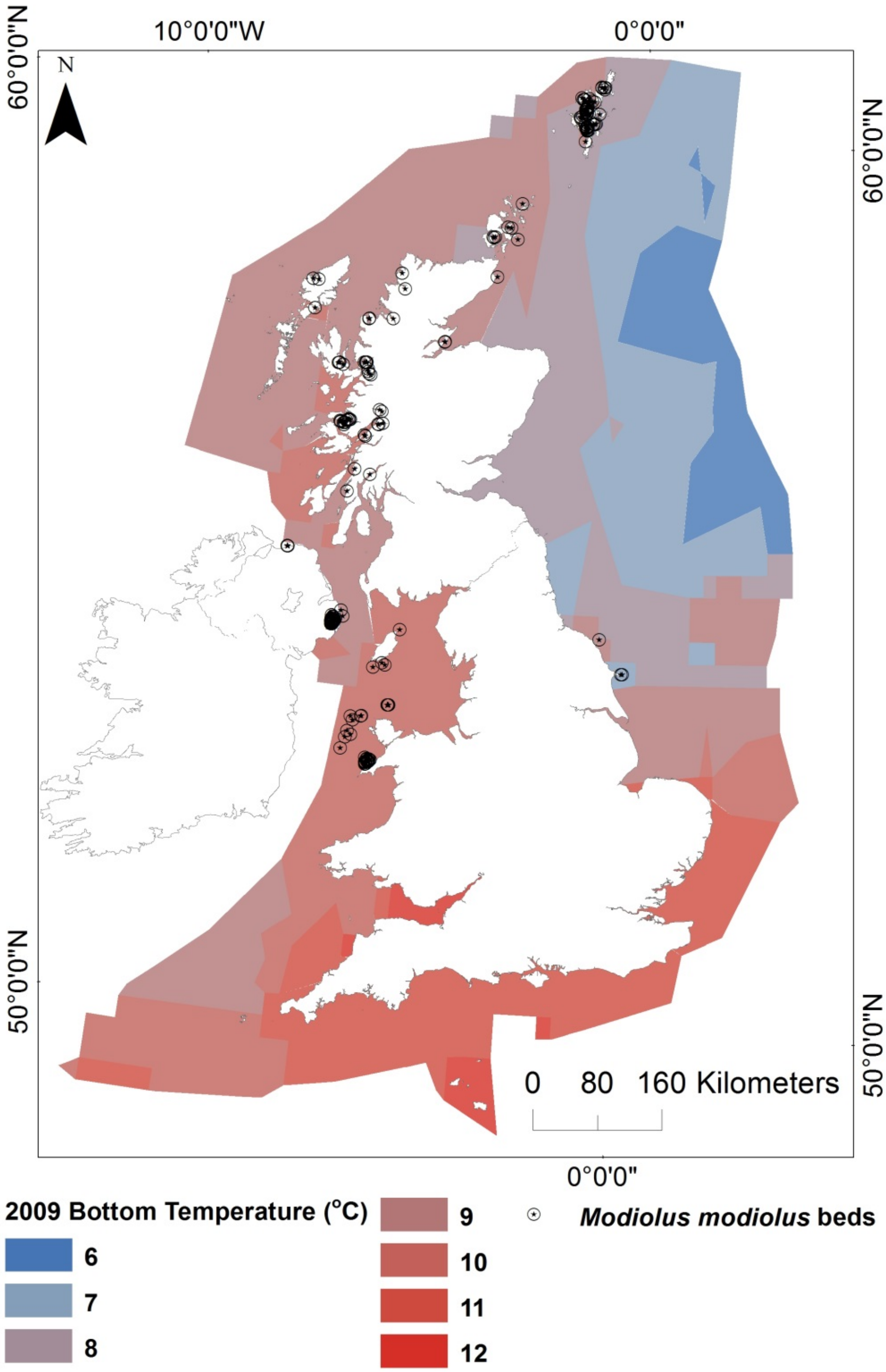


Figure 4.1: Study area, current known distribution of *Modiolus modiolus* beds and illustrated baseline (2009) seabed temperature (^{o}C); yearly average. Projection: WGS 1984 UTM 31N

4.2.3 Increased Ocean Temperature Scenario

Increased ocean temperature scenarios were established for the following epochs: 2009 (Figure 4.1), 2030, 2050, 2080 and 2100 based on Locarnini *et al*. (2010) and the International Panel on Climate Change (IPCC) scenario planning methodology (IPCC, 2007). Predictions were based on the IPCC climate change scenario A1B in which a 4^{o}C increase in ocean surface temperature would occur by 2100 (IPCC, 2007). A linear increase in ocean bottom temperature was calculated between 2009 and 2100, therefore increases of 0.92^{o}C, 1.80^{o}C and 3.12^{o}C were expected for 2030, 2050 and 2080 respectively (see Chapter 3 for more details).

Model scenarios assumed a uniform increase in temperature over the entire spatial domain and throughout the water column.

4.2.4 Environmental Envelope Analysis

Initial baseline species distribution analysis was carried out through the creation of an environmental envelope for *M. modiolus* bed populations in ArcMap 9.3. The *M. modiolus* bed occurrence records were grouped into populations based on their location and proximity to each other. Populations were selected if the occurrence records were within 10km of each other, excluding areas of obvious boundaries, e.g. land or sealochs etc. Within this 10km population grouping, the individual occurrence records were given a 1km buffer which would represent bed extent within that particular population. Environmental layers were plotted in vector format and overlaid with the population records. The "preferred range" of environmental attributes was characterised in terms of the interquartile ranges of the environmental variable values over the occurrence locations.

The "preferred range" for the landscape was calculated based on qualitative data (therefore the interquartile range calculation within ArcMap was not suitable as numerical data were not able to be calculated). The area of overlap for each population and landscape type was calculated. The percentage of each landscape type inhabited by a population was calculated (landscape range), ranked, then the median and maximum of these percentages (landscape range) was determined. The "preferred" landscape types were determined as representing those that were inhabited by the majority of the populations (≥ the median of the landscape range). This approach was taken because of the disparate nature of the population data.

Areas where "preferred range" attributes occurred for all overlying environmental layers were classed as the environmental envelope for horse mussel beds.

4.2.5 Species Distribution Model

Maxent is a predictive method that models the geographic distribution of species using presence-only data. Probability of occurrence is modelled in relation to environmental variables under the assumption that the species distribution will follow the property of maximum entropy (Phillips *et al.*, 2006; Phillips and Dubik, 2008; Jones *et al.*, 2012). Maxent has been used in a number of comparative studies examining the effectiveness of species distribution modelling (SDM) in the marine environment (Jones *et al.*, 2012; Reiss *et al.*, 2011; Ready *et al.*, 2010) and is considered to be reliable in the context of the marine environment (Reiss *et al.*, 2011).

Model Validation

The model predictions were tested using the 'Area Under the Curve' (AUC) produced by Maxent. The area under the receiver operating characteristic (ROC) curve is a widely used test statistic which measures model performance (Jones *et al.*, 2012). The AUC varies between 0 and 1, with values above 0.9 indicating excellent prediction, between 0.7 and 0.9 indicating good prediction, below 0.7 indicating poor prediction, and below 0.5 no better than random (Reiss *et al.*, 2011).

Owing to the lack of independent test datasets, models were assessed by 2-fold cross validation on ten replicate runs (Jones *et al.*, 2012). The occurrence dataset was randomly split in ArcMap 9.3 using the Hawths Analysis Tools for ArcGIS extension (Beyer, 2004) each containing a randomly selected 75% of records for model training and the corresponding 25% for model testing. A further model cross-validation was run using the full occurrence dataset randomly split into a 90% training/10% test dataset internally using the Maxent random test setting on a single run.

No absence data were available therefore, 10,000 randomly chosen pseudo-absence/background points were run. True absence data identified in Chapter 3 were not used as these points represented individual *M. modiolus* specimens, and not *M. modiolus* beds. Selecting the background points from the whole study area may artificially inflate the AUC value, especially if the geographic area is particularly large or the area of suitable habitat is small in relation to the whole study area (Jones *et al.*, 2012). During model evaluation, models were tested using background points selected from within a 20km buffer of the known occurrence locations (bias model) and compared with models run with background points selected from the whole study area (global model).

It was considered that the landscape layer might artificially influence the distribution of suitable habitat within the model, therefore, jack-knife contributions of each variable were measured to test the contribution of each variable to the model.

The tested models were visually inspected and compared to the environmental envelope analysis, and occurrence data. This enabled the assessment of model plausibility with respect to the known distribution and areas of suitable habitat outside known occurrence range (over-prediction) (Jones *et al.*, 2012).

Probability of Habitat Distribution

The probability of occurrence values (0 to 1) estimated in the Maxent model training and projection runs were separated into 10 bands and the area (Km^2) covered by each band was calculated.

The 10 probability bands were further separated into 3 categories for MPA region assessment:

i.) 0.5 – 1.0 representing a situation where *M. modiolus* beds may be more likely to occur ("most suitable habitat");

ii.) 0.1 - 0.49 representing a situation where *M. modiolus* beds are less likely to occur ("less suitable habitat"); and

iii.) 0.0 – 0.09 representing a situation where *M. modiolus* beds are highly likely not to occur ("unsuitable").

In this study, MPA regions are defined as designated regions of search for potential MPAs within UK waters (200nm limit).

4.3 Results

4.3.1 Environmental Envelope Analysis

The environmental envelope analysis method was applied to the *M. modiolus* bed population locations (Figure 4.1) and is a simple summarisation of potential suitable habitat for *M. modiolus* beds within UK waters. Table 4.2 outlines the environmental envelope calculated for *M. modiolus* beds.

Table 4.2: The selected Environmental Envelope for *Modiolus modiolus* (Linnaeus, 1758) beds.

Environmental Layer	Preferred Range
Temperature:	9 to 10 ^{o}C
Landscape:	Sealoch Shallow coarse sediment plain - moderate tide stress Shallow coarse sediment plain - weak tide stress Shelf coarse sediment plain - moderate tide stress Shallow sand plain Embayment Shallow mixed sediment plain - weak tide stress Shallow mud plain Shelf coarse sediment plain - strong tide stress Photic rock
Bathymetry:	-20 to 0 m
Current Speed:	0.5 to 1.115 m/s
Slope:	0 to 0.345%
Salinity:	34 to 35 ppt

Figure 4.2 illustrates the environmental envelope for *M. modiolus* beds and represents areas of suitable *M. modiolus* bed habitat generated by the envelope analysis.

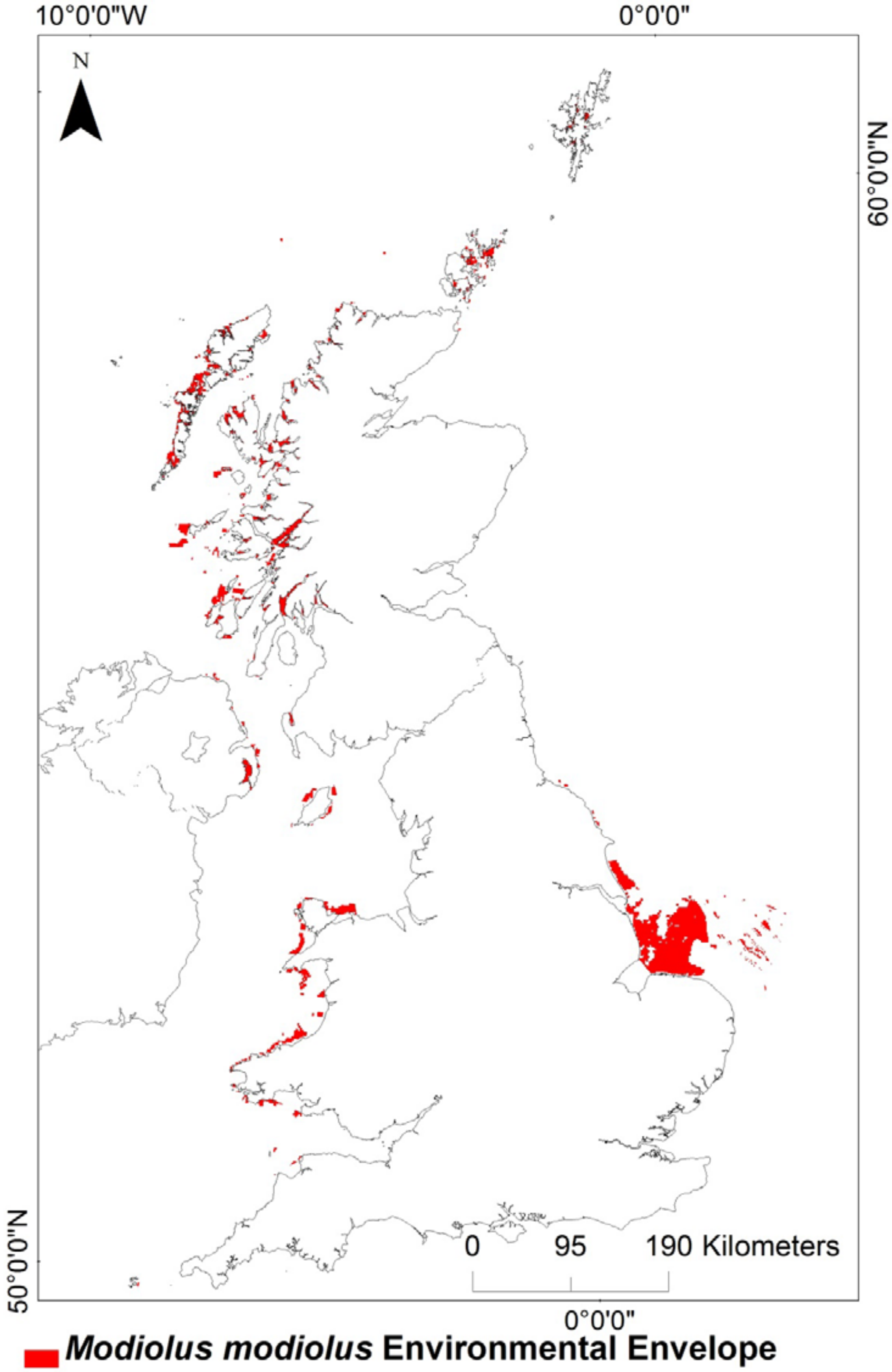


Figure 4.2: ArcMap calculated Environmental Envelope for *Modiolus modiolus* beds. Projection: WGS 1984 UTM 31N

This method indicates that the west of Scotland, Strangford Lough in Northern Ireland, Wales, Orkney and Shetland are the most suitable areas for *M. modiolus* beds, with more scattered areas around the Isle of Man. The east coast of England (North Norfolk) represents a large expanse of potentially most suitable habitat *M. modiolus* habitat.

When the envelope analysis was applied to the projected climate change scenarios, results indicated that there would be a decrease of potentially suitable habitat by 2050 (58% loss by 2030; and 98% loss by 2050) and complete loss of suitable *M. modiolus* bed habitat by 2080.

The envelope analysis was re-run for the baseline model (using data outlined in Table 4.1), excluding the landscape environmental layer (to test for environmental variable bias) and a small increase in suitable habitat was noted, however, results still showed the same distribution pattern as before, with a slight increased presence around the coast of Wales, east England and south west Scotland. This comparison suggests that the landscape layer did not have a disproportionate effect on the baseline model outcome.

4.3.2 Species Distribution Model

Model Selection

The Maxent model was trained using cross-validation of two externally selected sub-sets of the 2009 baseline data and further trained for an internally selected sub-set within Maxent's automated validation test. The training AUC values, shown in Table 4.3, ranged from 0.89 to 0.99 with little variation shown over the 10 replicates (maximum difference from 0 to 0.006). The test AUC values ranged from 0.85 to 0.98 and showed slightly higher variation over the replicated runs (maximum difference 0.008 to 0.062).

Table 4.3: Threshold-independent area under the curve (AUC) indices for *Modiolus modiolus* (Linnaeus, 1758) habitat model.

	Average AUC Test Statistic			
	Training		Testing	
Model (Training/Test)	**Bias**	**Global**	**Bias**	**Global**
Set 1 (75/25%)	0.92 ±0.003	0.98 ±0.001	0.86 ±0.051	0.97 ±0.023
Set 2 (75/25%)	0.94 ±0.003	0.99 ±0.001	0.90 ±0.047	0.97 ±0.043
All (90/10%)	0.93 ±0.006	0.99 ±0.000	0.92 ±0.039	0.98 ±0.008
Final model (90/10%)	**0.93**	**0.99**	**0.88**	**0.97**

Test statistic values decreased when calculated using pseudo-absences restricted to 20 km from occurrence records.

A final model was run for each of the sampling scenarios using the full occurrence records and a 90%/10% training/test ratio run on a single replicate. The AUC values for the final model ranged from 0.92 to 0.99 for model training and 0.88 to 0.97 from model testing and generally equalled the average of the cross-validated models, indicating little variation between the overall model test statistics. Overall, the environmental variable with the highest gain when used in isolation was landscape, which therefore appears to have the most useful information by itself when determining the location of suitable habitat. In contrast, when bathymetry was omitted the jack knife analysis showed the lowest gain, indicating that the bathymetry variable has the most information not present in the other variables, when determining location of suitable habitat. The AUC values remained above 0.96 for each model run following omission of each environmental variable in turn; this indicates 'excellent' model performance.

Pseudo-absence selection models were compared. The models where pseudo-absences were chosen from within 20km of the known occurrence records predicted suitable habitat to occur to the west of Scotland and Northern Ireland, but with the highest probability of suitable habitat occurring on the North Norfolk sandbanks. There were also areas of low probability predicted in the English Channel and a lack of suitable habitat predicted around Orkney (Figure 4.3). In comparison, in the models where pseudo-absences were selected from the whole study area, the highest probability of suitable habitat occurring was observed predominantly to the West of Scotland, Shetland and Northern Ireland. The area around the Norfolk sandbanks showed lower levels of probability (Figure 4.4).

The “most suitable” habitat output (probability ≥0.5) for 2009 from Maxent were compared with the environmental envelope.

The output of the Environmental Envelope Analysis (EEA) showed a 50% overlap of the "most suitable" habitat predicted by the Maxent global sampling model; with an overlap of 22% of the "less suitable" habitat and <1% of the “unsuitable” habitat (Table 4.4). These data provide a comparison of the two utilised models and indicates that the majority of the models overlap with one another, providing a process for model validation.

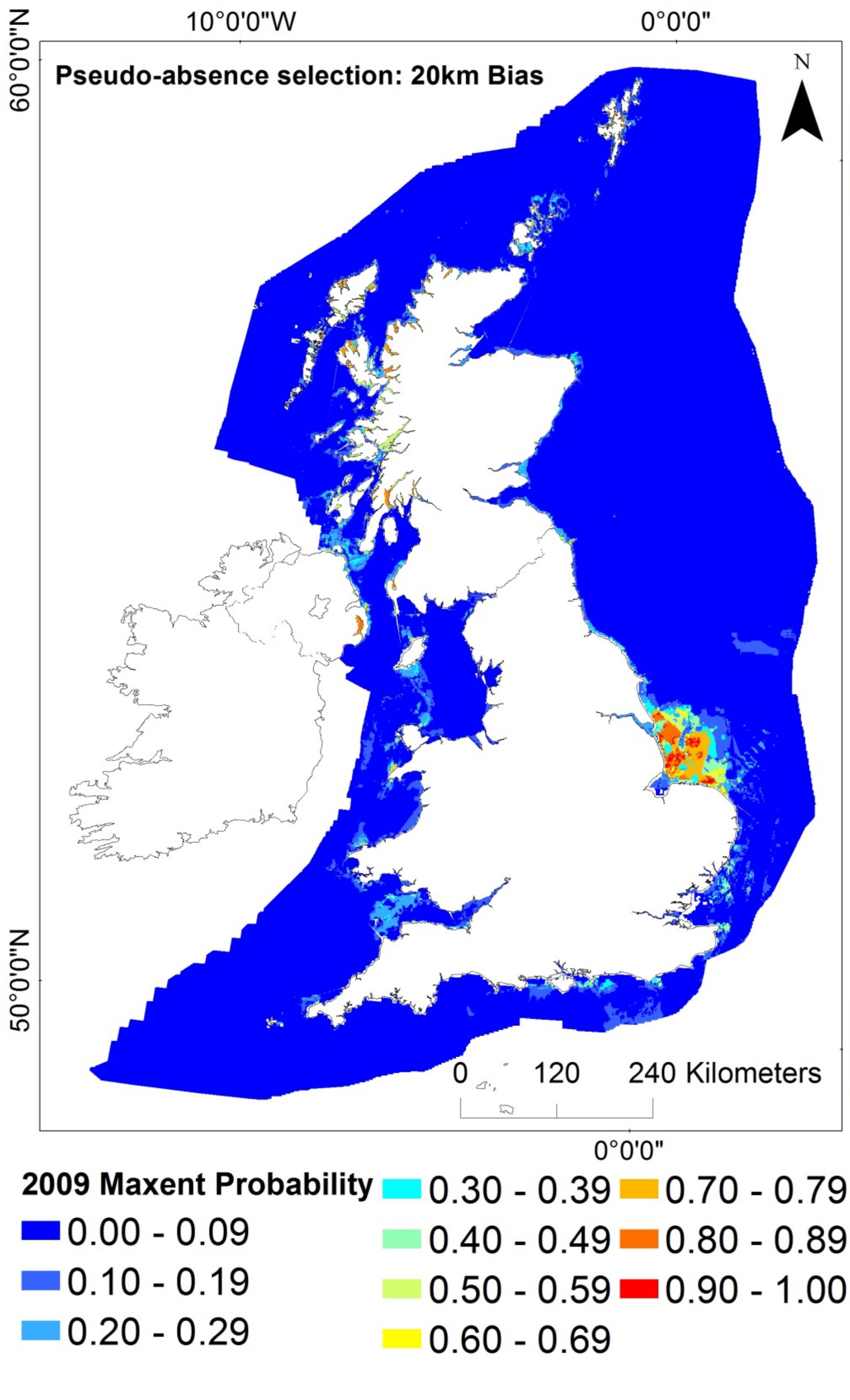


Figure 4.3: Full model prediction map (Maxent output) for *Modiolus modiolus* beds under baseline conditions (2009). Model sampling bias: 20km. Projection: WGS 1984 UTM 31N

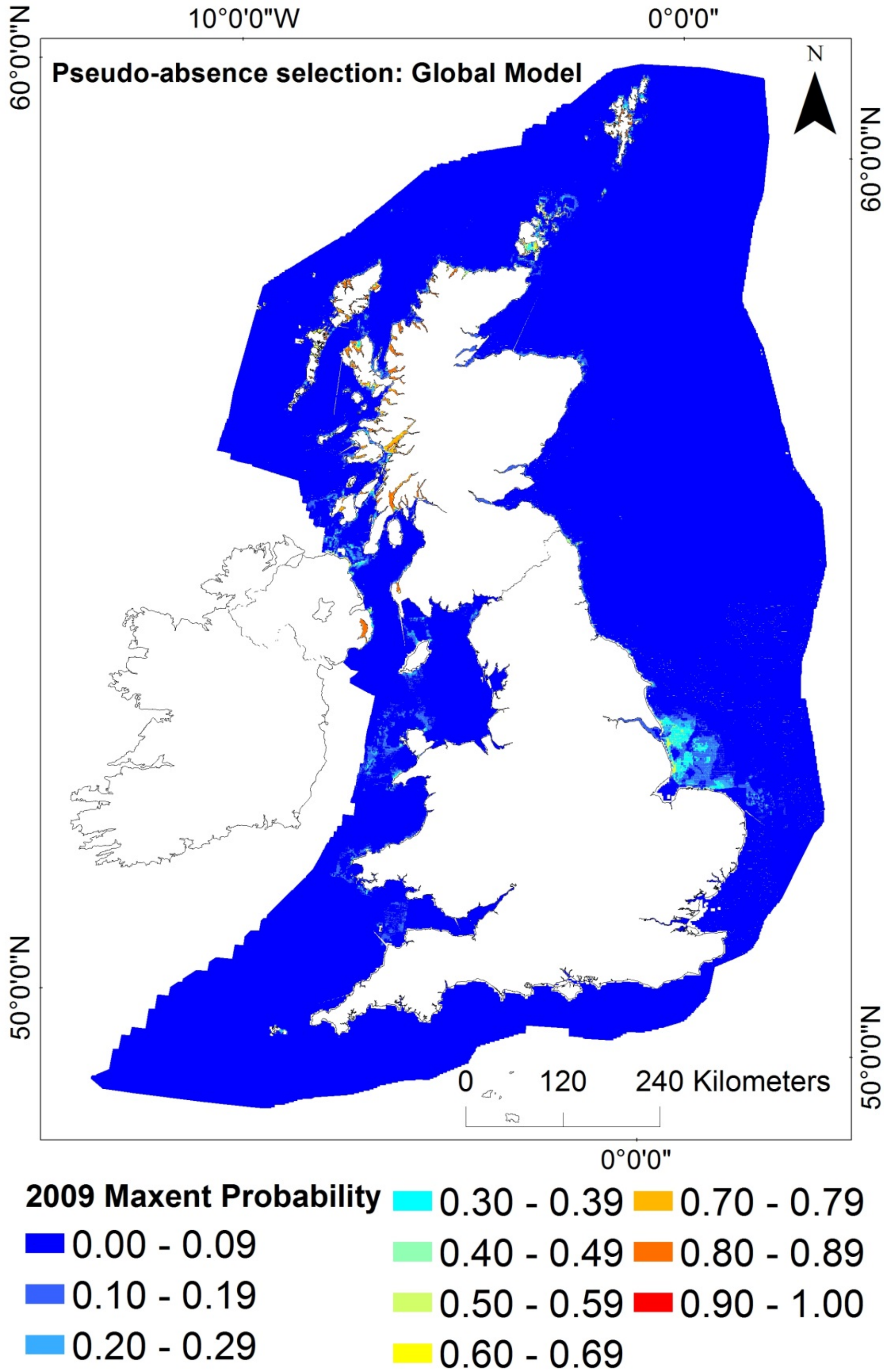


Figure 4.4: Full model prediction maps (Maxent output) for *Modiolus modiolus* beds under baseline conditions (2009). Model sampling bias: Global. Projection: WGS 1984 UTM 31N

Table 4.4: Comparison of Environmental Envelope Analysis and Maxent model outputs. Overlap area calculations

<table>
<tr><th colspan="2">Method/Model</th><th>Area (Km^2)</th><th>Percentage of Maxent overlapped by envelope</th><th>Combined overlap (excluding "unsuitable" habitat)</th><th>Percentage "over prediction" (model vs envelope)</th></tr>
<tr><td colspan="2">Envelope Analysis</td><td>7,009</td><td>n/a</td><td>n/a</td><td>n/a</td></tr>
<tr><td rowspan="2">Global model</td><td>"Most Suitable"</td><td>2,191</td><td>50%</td><td rowspan="2">26%</td><td rowspan="2">58%</td></tr>
<tr><td>"Less Suitable"</td><td>14,390</td><td>22%</td></tr>
<tr><td rowspan="2">Bias model</td><td>"Most Suitable"</td><td>6,471</td><td>55%</td><td rowspan="2">16%</td><td rowspan="2">81%</td></tr>
<tr><td>"Less Suitable"</td><td>29,659</td><td>8%</td></tr>
</table>

Model Projections

The selected baseline model was projected against the predicted 2030, 2050, 2080 and 2100 conditions. Figure 4.5 illustrates that the percentage of sea area suitable for *M. modiolus* beds decreases rapidly over the 4 projected epochs with a 100% loss of *M. modiolus* bed habitat predicted by 2100. The 10 probability bands were separated into 3 categories for ease of examination and discussion: “most suitable” (MS), “less suitable” (LS) and “unsuitable” (US) habitat. Calculated areas indicated a 100% loss of “most suitable” habitat by 2080 (Figure 4.5). Figure 4.6 illustrates the rapidity of habitat loss of the epochs. The steepest decline of potential habitat occurs in bands 0.1 to 0.39 between 2050 and 2080, and band 0.8 to 0.89 between 2030 and 2050. The modelled projections are illustrated in Figure 4.7. The extent of predicted distribution as represented by the shading decreases significantly over the 4 epochs.

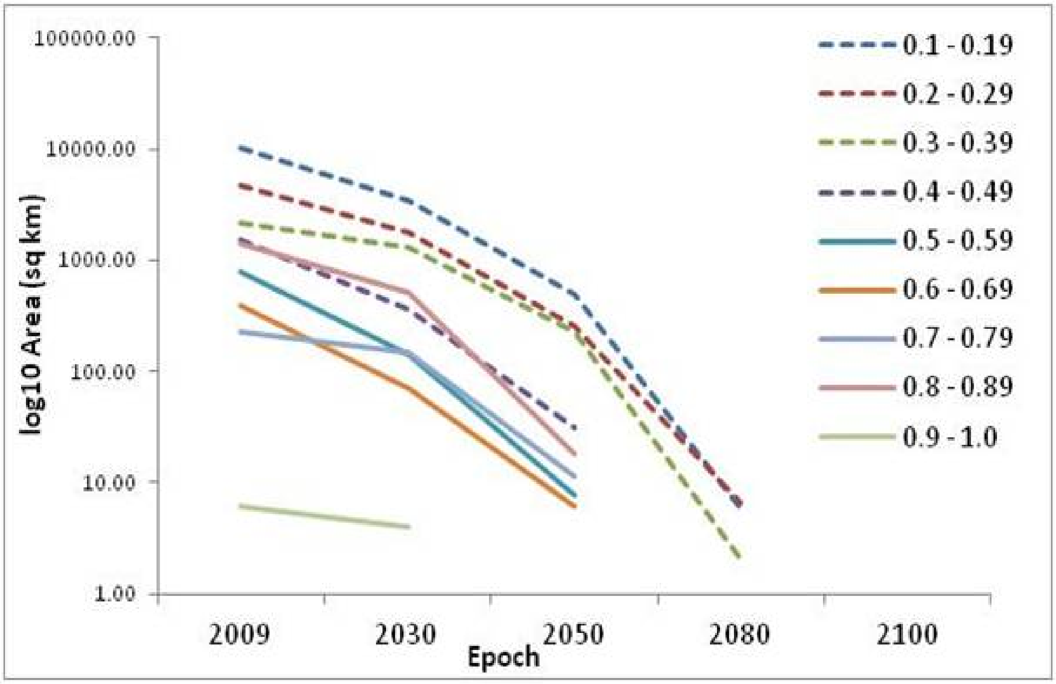


Figure 4.5: Percentage of area suitable for *Modiolus modiolus* habitat based on different probability scenarios.

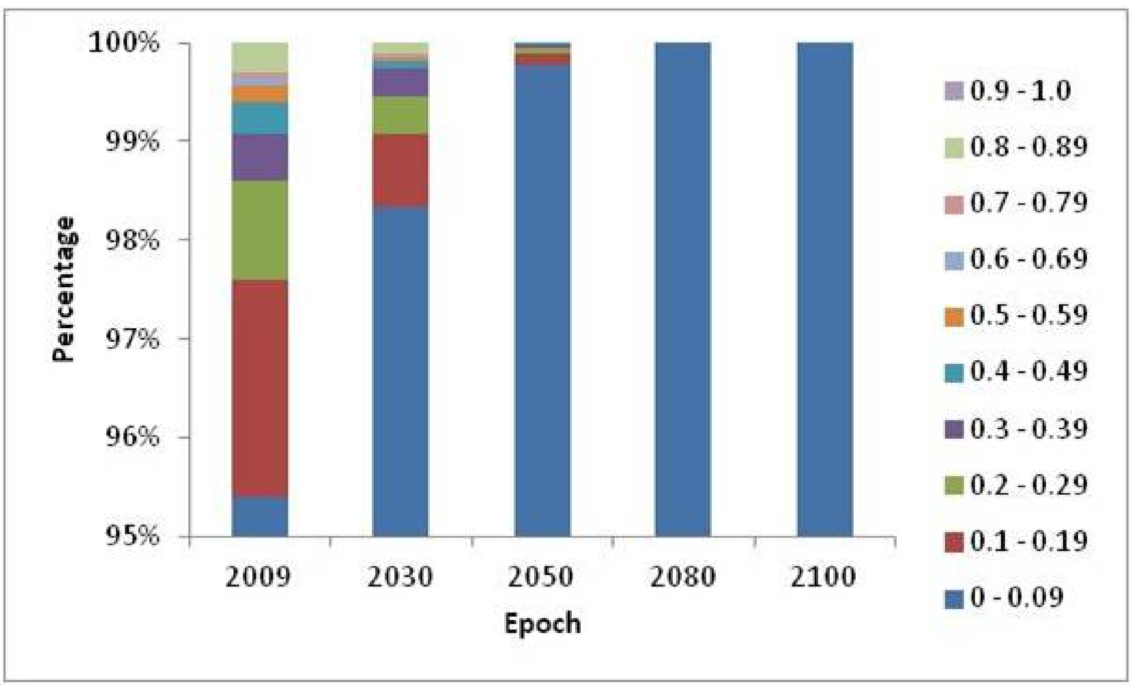


Figure 4.6: Change in suitable *Modiolus modiolus* habitat occurrence area (Km2) (Log10) between 2009 and 2100. Illustration of speed of habitat loss.

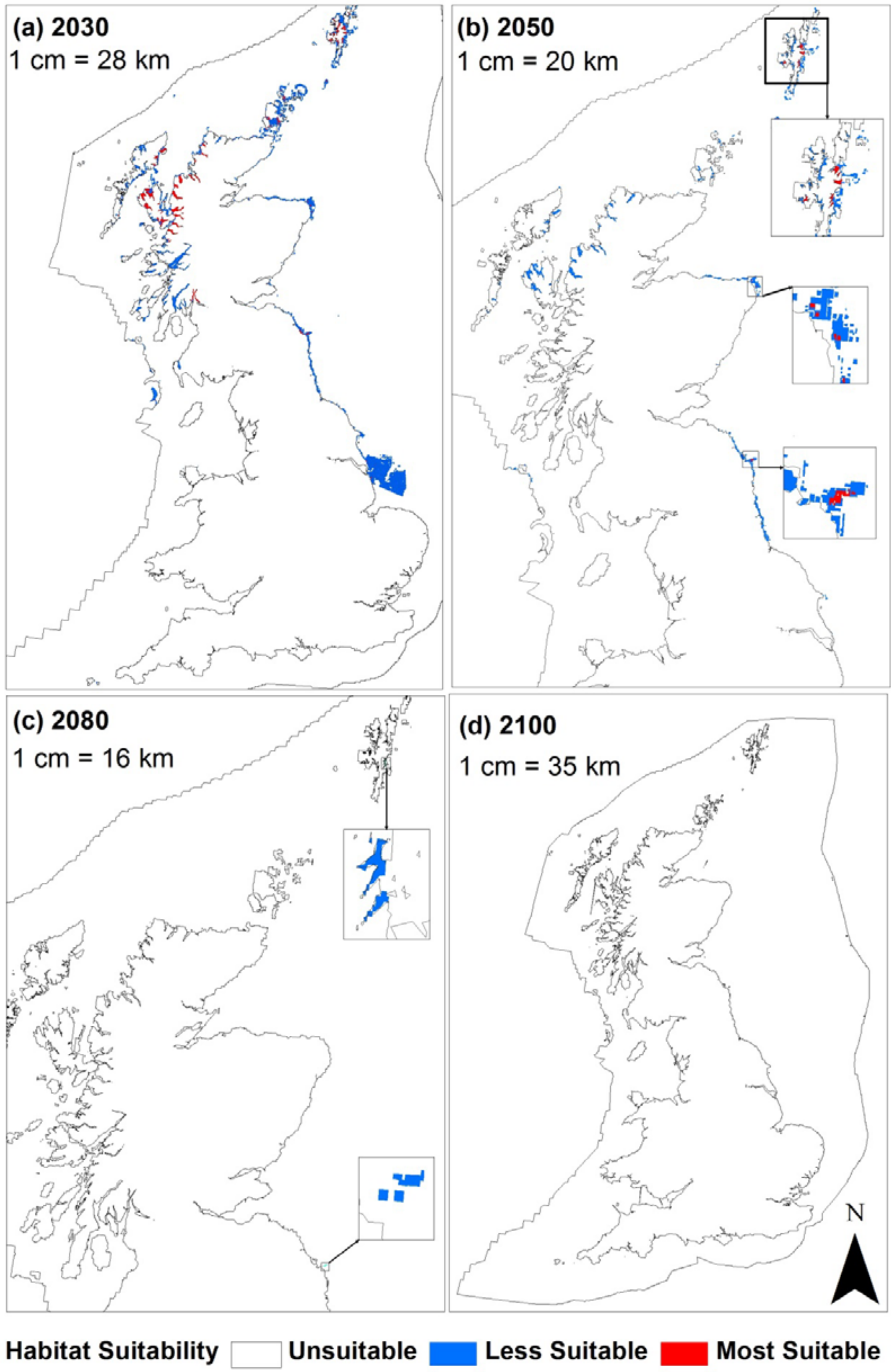


Figure 4.7: Full model prediction maps for *Modiolus modiolus* beds for the 4 projected climate change epochs (a) 2030, (b) 2050, (c) 2080 and (d) 2100. Projection: WGS 1984 UTM 31N

4.3.3 MPA Region Assessment

The area of MS, LS and US habitat within each MPA region was calculated over the 5 epochs and these data are summarised in Table 4.5. The results show that there are some MPA regions that are potentially more important to *M. modiolus* beds than others. The area and percentage loss of "most suitable" habitat within each MPA region is summarised in Table 4.6. The results (Tables 4.5 and 4.6) show that the West of Scotland (Territorial) MPA region is the most important region in terms of predicted habitat. The Net Gain, North Scotland (Territorial), South West Scotland (Territorial) and Northern Ireland are also important regions. Most significantly, the West of Scotland (Territorial) region loses 56% of its "most suitable" habitat by 2030 and 100% is lost by 2050. A map illustrating the location of the MPA Regions is shown in Figure 4.8.

Table 4.5: The area of "most suitable" (ms), "less suitable" (LS) and "unsuitable" (US) habitat within each MPA region

MPA Region	Area (Km^2)															
	2009			2030			2050			2080			2100			Total area of region
	MS	LS	US	MS	LS	US	MS	LS	US	MS	LS	US	MS	LS	US	
East Scotland	0	0	98761	0	0.00	99204	0	0	98961	0	0	99242	0	0	99210	101511
East Scotland (Territorial)	20	923	12391	11	817	12537	4.83	151	13167	0	0	13386	0	0	13380	13656
Balanced Seas	0	6	15013	0	0	15282	0	0	15294	0	0	15273	0	0	15202	17846
Finding Sanctuary	3	931	77999	0	2	79059	0	0	78739	0	0	79391	0	0	79028	95979
Irish Sea Conservation Zone	10	1493	15485	0	9	16687	0	0	16833	0	0	16730	0	0	16700	17551
Isle of Man	7	601	3159	0	6	3774	0	0	3780	0	0	3780	0	0	3780	4609
MCZ Project Wales	24	2283	13627	0	8	15917	0	0	15918	0	0	15951	0	0	15946	16375
Net Gain	583	7031	103228	81	3300	107776	6.50	213	111024	0	0	110931	0	0	111117	113204
North Scotland	0	0	22742	0	0	23247	0	0	23185	0	0	23130	0	0	23194	29967
North Scotland (Territorial)	324	1540	21361	136	1229	21662	32	232	22708	0	0	22996	0	0	23018	23860
Northern Ireland	210	683	3197	0	153	4090	0	21	4196	0	0	4160	0	0	4234	9071
South West Scotland (Territorial)	273	766	6538	37	258	7319	0	0	7598	0	0	7644	0	0	7645	7996
West Scotland	0	93	16698	0	0	17165	0	0	16650	0	0	17156	0	0	16942	27701
West Scotland (Territorial)	1345	2311	36913	590	1074	39231	0	382	40435	0	0	40698	0	0	40742	43640

Table 4.6: The area and percentage loss of "most suitable" habitat within each MPA region

MPA Region	2009	2030		2050		2080		2100	
	Area	Area	% Loss	Area	% Loss	Area	% Loss	Area	% Loss
East Scotland	0.00	0.00	n/a	0.00	n/a	0.00	n/a	0.00	n/a
East Scotland (Territorial)	19.91	10.71	46	4.83	76	0.00	100	0.00	100
Balanced Seas	0.00	0.00	n/a	0.00	n/a	0.00	n/a	0.00	n/a
Finding Sanctuary	3.20	0.00	100	0.00	100	0.00	100	0.00	100
Irish Sea Conservation Zone	10.28	0.00	100	0.00	100	0.00	100	0.00	100
Isle of Man	7.29	0.00	100	0.00	100	0.00	100	0.00	100
MCZ Project Wales	24.11	0.00	100	0.00	100	0.00	100	0.00	100
Net Gain	582.81	80.86	86	6.50	99	0.00	100	0.00	100
North Scotland	0.00	0.00	n/a	0.00	n/a	0.00	n/a	0.00	n/a
North Scotland (Territorial)	323.64	136.15	58	31.72	90	0.00	100	0.00	100
Northern Ireland	210.26	0.00	100	0.00	100	0.00	100	0.00	100
South West Scotland (Territorial)	273.09	36.97	86	0.00	100	0.00	100	0.00	100
West Scotland	0.00	0.00	n/a	0.00	n/a	0.00	n/a	0.00	n/a
West Scotland (Territorial)	1345.32	590.39	56	0.00	100	0.00	100	0.00	100

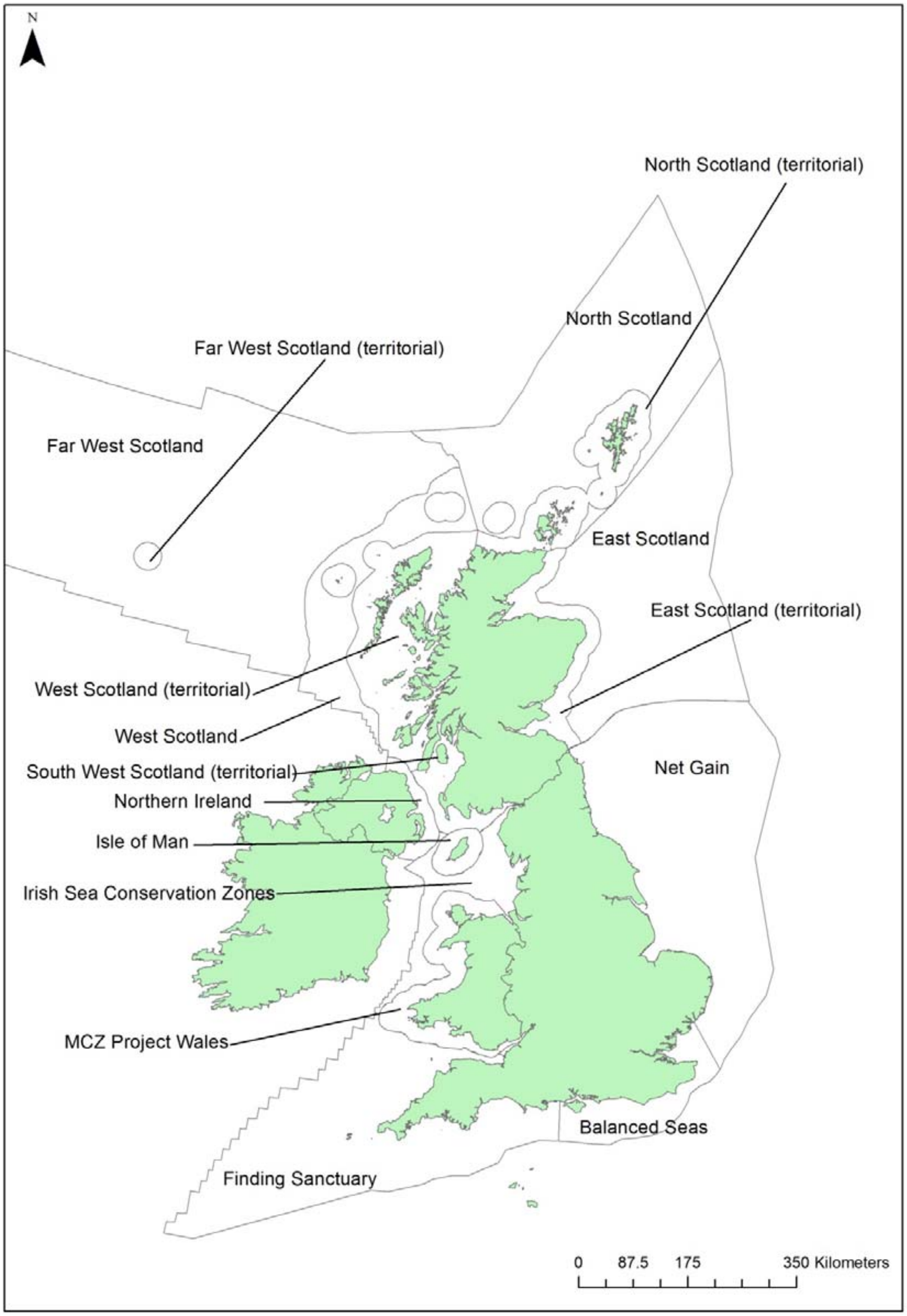


Figure 4.8: UK Marine Protected Areas Regions

4.4 Discussion

The aim of this study was to model the ecological niche and bioclimatic envelope of *M. modiolus* beds within UK waters as a baseline for subsequent increased ocean temperature projections, and to demonstrate its application as a tool for future management of habitats. Species Distribution Modelling techniques have previously been applied in the marine environment to a range of motile species (Jones *et al.*, 2012; Reiss *et al.*, 2011; Hedger *et al.*, 2004; Macleod, 2010; MacLeod *et al.*, 2008; Lambert *et al.*, 2011); but, with the possible exception of Ross and Howell's (2012) study on deep sea organisms, this is the first study the authors are aware of that deals with marine habitat forming species of high conservation management interest, under an increasing ocean temperature scenario. In a terrestrial setting bioclimatic envelope models provide perhaps the best available guide for conservation managers and policy makers (del Barrio *et al.*, 2006; Carvalho *et al.*, 2011; Rose and Burton, 2009; Nativi *et al.*, 2009; Pearson and Dawson, 2003; Dawson *et al.*, 2011) and have been considered as first approximations of the magnitude and broad patterns of future impacts (Pearson and Dawson, 2003). In this context, terrestrial conservation protection has appeared inadequate under future climate change scenarios (Carvalho *et al.*, 2011). Carvalho *et* al. (2011) concluded that protected areas covered 10% of the current distribution of all Iberian herptiles; and that to maintain this coverage the protected area network would have to be increased by 1-2% by 2080.

4.4.1 Environmental Envelope Analysis

The environmental envelope analysis (EEA) provided a relatively quick and simple method for analysing the potential distribution of the *M. modiolus* habitat and was performed in order to validate the Maxent model method. The envelope analysis greatly improves the visualisation and analysis of potential projected conditions in support of conservation planning without the requirement for specialised modelling knowledge; and methods such as this demonstrate the possibilities of generating new knowledge from existing data sets. It was important that all environmental variable layers used were freely and publically available in order to demonstrate the immediate applicability of such modelling tools to inform contemporary policy and management decision making for the marine environment.

The envelope analysis, however, will only take into account areas where all the individual "preferred ranges" overlap, a concept that is corrected for within the Maxent model. In addition, the EEA does not lend itself sufficiently to model testing and statistical analysis; therefore it would not necessarily provide robust evidence, unless run alongside another model. It does however provide a robust representation of shifting habitats in a timely and cost-effective manner.

The EEA method developed within this study is, as far as the author is aware, a new use of the method for the selection of an environmental envelope based on the interquartile range analysed within a GIS setting. Two other proposed methods were also investigated (Jarnevich *et al.*, 2007; Powell *et al.*, 2005), but these methods were judged to be unsuitable for the data used within this particular study. These methods were either based on descriptive data and on species that inhabit a very particular niche (Powell *et al.*, 2005), or suggested too wide an envelope (minimum to maximum ranges) (Jarnevich *et al.*, 2007). See Chapter 3 for details and results of these methods.

The envelope analysis utilised, predicts that the habitat will retreat northwards as sea temperatures increase, with more limited extent of distribution in the Irish Sea and Shetland regions compared to the current known bed occurrence records (Figure 4.1). These results would suggest that although this type of analysis is useful for simple visualisation and summarisation of suitable habitat areas, more refinement of environmental layers is required for detailed application.

4.4.2 Species Distribution Model

The Maxent model outputs in this study provide an overview of potentially suitable *M. modiolus* bed habitat. Despite the present model being built on environmental variables with coarse resolution, species with a narrow ecological niche can show high accuracy of predicted distribution under modelled conditions compared to those with a broader niche (Reiss *et al.*, 2011). In addition, the global model which was utilised in this study closely resembled the output of the comparative environmental envelope analysis. Overall, therefore, the baseline trained model (global model) can be interpreted as a good predicted range, with projections showing that the *M. modiolus* beds lose their ability to fulfil that range by 2100. Under these modelled conditions *M. modiolus* beds in the UK will be increasingly vulnerable.

Details of climate change scenarios in the marine environment are poorly understood. The extent to which environmental changes (e.g. alterations to hydrodynamics and sediment dynamics) might occur alongside temperature increases is not well studied. Other environmental variables such as salinity and acidity were excluded in the present study because there was a lack of information (Harley *et al.*, 2006), or conflicting literature on the potential levels and direction of change in these variables (e.g. salinity increasing (Meredith and King, 2005; Dore *et al.*, 2003), salinity decreasing (Manabe and Stouffer, 1995); salinity decreasing at high latitudes and increasing at low latitudes (Jacobs, 2006; Curry *et al.*, 2003)). Under the climate change scenario A1B (IPCC, 2007) ocean pH is predicted to decrease to 7.9 from a baseline of 8.1 in 2007. However, no environmental data on the variability of pH of the seawater around the UK were readily available to allow this scenario to be defined in terms of spatial variation. Depth was excluded from the "climate change" scenario based on the quality of the bathymetry data used. The sea level rise predicted under the climate change scenario A1B indicates an increase of up to 0.5 m by 2100. Unfortunately, it is too difficult to comment on whether the lack of pH data is a major omission for modelling potential changes. There is simply not enough evidence or data to show what the variation is in baseline or retrospective baseline oceanic pH geographically.

It was considered that the omission of certain climate change environmental parameters, as discussed above, and the environmental parameters applicable to *M. modiolus* beds (e.g. water quality) was not a major issue. The overall resolution, geographic coverage, lack of data or general poor quality of these potential data sets would have diluted the outputs from the model. Water quality is used as a parameter at a wider European level as shown in the Chapter 5.

The assumptions made on increased ocean temperature at depth in the present study are supported by research conducted by Levitus *et al*. (2000). This research suggested warming of the upper 300m of the world's oceans between 1948 and 1998, particularly the Indian and Atlantic Oceans. However, it is unclear as to what magnitude ocean warming at depth will occur in the future; and variations in the speed of climate change between UK regions are unknown (Burrows *et al.*, 2011).

An issue with SDM techniques for sessile organisms like *M. modiolus* is that SDM, including Maxent, base predicted distributions on an ecological niche theory, and do not give consideration to propagule dispersal (Engler and Guisan, 2009), dispersal vectors and propagule establishment (Mokany *et al.*, 2010). Although knowledge of larval dispersal may not necessarily refine habitat suitability models in definite terms, it may lead to an enhanced understanding of model predictions or contribute to model accuracy.

Presently, little information is available on genetic connectivity of the beds. Holt *et al.*(1998) and Comely (1978) suggest recruitment from outside the area for beds off the Llyn Peninsula and the Isle of Man; and self-sustaining populations occurring in Strangford Lough and the Scottish sealochs based on perceptions of wide dispersal from and to highly tidal areas, and low dispersal from and to sealochs with high water residence times. Habitat connectivity of *M. modiolus* beds is addressed in Chapter 7.

M. modiolus are thought to spawn in a relatively narrow temperature window (7-10^{o}C) (Brown, 1984) suggesting that, although the model shows a reduction of potentially suitable *M. modiolus* habitat, recruitment may be the mechanism by which reefs cease to be viable. Established reefs may therefore persist beyond the prediction of the present study, but their reproduction may be hindered; and local adaption to the changing climate may occur over time.

M. modiolus are relatively long lived, with a life-span of approximately 20-100 years (Rees, 2009a) giving some indication of the lag-time before senescence might be detected. There is, as yet, no evidence of reefs that are senescing. Many beds studied in the 1950s still exist (Seed and Brown, 1975; Seed and Brown, 1978; Sanderson, unpubl.; Hill *et al.*, 2010) and reefs in North Wales are thought to have persisted for approximately 150 years (Lindenbaum *et al.*, 2008), with evidence that these beds are still recruiting (Hill *et al.*, 2010). Studies have recorded an overall decline in the extent of *M. modiolus* beds in the period between 1950 and 1990 (Rees, 2009a).

The trained model output illustrated that the most suitable baseline areas occurred in west Scotland, Northern Ireland (Strangford Lough) and Shetland, with less suitable habitat occurring in the Irish Sea and Orkney. At first thought, patches of suitability around the east coast of England (Norfolk coast) appear misleading because beds are not known to occur there (Figure 4.7). It is possible that the model is predicting the existence of suitable environmental conditions for *M. modiolus* beds in in this area, but other unaccounted factors (e.g. connectivity, fishing impacts, or turbidity etc.) could be preventing actual bed presence. Limitations of knowledge, low numbers of targeted surveys or decline of beds in this area are also possible explanations. For example, the Southern North Sea, the Western Channel/Celtic Sea and Irish Sea are known to have the highest intensity of trawling and dredging pressure in the UK (Aish *et al.*, 2010): an anthropogenic pressure thought to impact these biogenic habitats (e.g. Strain (2012)). Furthermore, the North Norfolk Sandbanks and Saturn Reef are designated MPAs (Special Area of Conservation; SAC) for *Sabellaria spinulosa* Leuckart, 1849 beds, a tube dwelling polychaete, which requires silty, turbid conditions to build their tubes and reefs (Holt *et al.*, 1998). In this study the model may therefore be interpreting the suitability of areas for biogenic reefs and may not be refined enough to distinguish the environmental envelope for functionally similar species structures. *S. spinulosa* require suspended sediment to build their tubes, *M. modiolus* do not, and may be sensitive to smothering and/or lack of suitable suspended food.

Interestingly, surveys carried out in relation to wind farm developments in the North Norfolk area in the months following this study showed areas of live and dead *M. modiolus* in quantities that indicate the presence of a bed, or at least that a bed was present at some point. This confirmation (Figure 4.9) ground truths/confirms that perhaps both model predictions for this region are in fact correct and represent suitable *M. modiolus* bed habitat, despite earlier reservations.

Figure 4.9: Humber REC Area potential *Modiolus modiolus* bed

Source: Marine Environmental Surveys (MES) Ltd on behalf of Marine Environment Protection Fund (MEPF) as part of the Humber REC Survey

4.4.3 MPA Region Assessment

The area of the current SACs that encompass *M. modiolus* beds (Loch Creran and Lochs Duich, Long and Alsh beds, west Scotland; the Lleyn Peninsula and Sarnau, north Wales; Sanday, Orkney; Strangford Lough, Northern Ireland) cover 141Km^2 of the predicted distribution of "most suitable" habitat in 2009; 15Km^2 in 2030 and zero in 2050 to 2100. This represents 8% protection of the predicted "most suitable" habitat range in 2009 and this drops to 0.9% by 2030; and 0% by 2050. Protection is therefore limited, and will dwindle in contrast to the Convention on Biological Diversity target: "*By 2020, at least ….. 10% of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services, are conserved through ……. representative and well-connected systems of protected areas and other effective area-based conservation measures….*" (Convention on Biological Diversity, Strategic Goal

C: To improve the status of biodiversity by safeguarding ecosystems, species and genetic diversity, Target 11). Although, this statement is not species specific, the IUCN's Vth World Parks Congress, 2003, suggested that 20-30% of each habitat should be protected within MPAs by 2012 (Ross and Howell, 2012; CBD, 2010; IUCN, 2003; Metcalfe *et al.*, 2013; Holt *et al.*, 1998).

Micheli *et al.* (2012) concluded that the protection afforded to species in marine reserves supports population resistance to large scale environmental impacts. This is achieved through greater larval production and recruitment; large adult body size; absence of fishing related mortality and larval spill-over; maintained reproductive output; and recoverability. A network of marine protected areas may therefore be the most effective tool in mitigating the negative impacts of climate change on marine ecosystems and their associated livelihoods (Micheli *et al.*, 2012).

In addition to designated protected areas, consideration also needs to be given to potential dispersal corridors (Rose and Burton, 2009) to accommodate movement of conservation interest species/habitats within a changing climate, potentially safeguarding these areas through conservation easement (Thomas *et al.*, 2012).

4.4.4 Pan-European perspectives

Presently, UK Good Environmental Status (GES) targets under the MSFD for rock and biogenic beds are drawn from the Habitats Directive (HM Government, 2012) i.e. that the *"Area is stable or increasing and not smaller than the baseline value"* (EU Habitats & Species Directive, Council Directive 92/43EEC). This is in keeping with one of the key aims of the MSFD to *"Protect and preserve the marine environment prevent its deterioration or, where practicable, restore marine ecosystems"* (Marine Strategy Framework Directive, Council Directive 2008/56/EC). However, one of the key MSFD characteristics of Biodiversity (Descriptor 1) is that *"The quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic and climatic conditions"*, a characteristic that is being interpreted as accommodating climate change (HM Government, 2012; Moffat *et al.*, 2011). The implication of the present study is that, in the short term, maintaining nationally "stable or increasing" areas of some protected habitats may not be achievable within the next 40 years without significant restorative and facilitated migration work. For habitats like these, the connectivity of an MPA network will be of paramount importance, especially for those that have already suffered historic loss and fragmentation. It is also possible that within a life time, maintaining "stable" areas may not be achievable at all within a national or regional context.

The amount of habitat loss that would be tolerated within the assessment of GES under the MSFD is yet to be defined for many target species/habitats and methods such as the one demonstrated within this study, could, with further refinement enable more plausible definition of targets.

4.5 Conclusions

Paradoxically, the achievement of GES within 'prevailing climatic conditions' may require European Atlantic nations to manage the decline and migration of some of their marine habitats of biodiversity conservation importance rather than maintain their present extent. This concept is relatively novel to marine conservation management and not currently represented within national or international Marine Spatial Planning; nor in the conservation objectives or management plans of MPAs.

4.6 Chapter 4 Summary

- Existing data can be used to develop species distribution modelling scenarios for the projected movement of benthic habitat forming species
- Results showed that there may be a potential loss of *Modiolus modiolus* beds in the UK by 2100
- Results can be incorporated into policy strategies particularly for conservation targets, such as MPAs in order to prioritise areas and set appropriate management strategies
- This study leads to futher questions, particularly – is there actually a complete loss of *Modiolus modiolus* beds by 2100? Or do they simply move northwards? And what will happen to the other Priority Marine Habitats?
- A further study was developed to expand this tested method to a wider geographic area: Chapter 5

Chapter 5. Predictive Habitat Modelling of OSPAR Priority Marine Habitats in Europe

5.1 Introduction

With the adoption of the Marine Strategy Framework Directive 2008/56/EC (MSFD) in 2008 came the introduction of a European-wide integrated approach to marine environmental protection (Salomon and Dross, 2013). The past decade has seen a dramatic rise in the number and size of Marine Protected Areas (MPAs) being designated by nations as a result of international environmental protection targets (De Santo, 2013); and it could be argued that Europe has potentially been the most active in establishing regional management strategies (Narayanaswamy *et al.*, 2013). While nations are understandably concerned with their own marine environment first and foremost, some consideration of the potential future movement, expansion and contraction of habitats and species of conservation importance (as a result of changing climatic conditions) between different Economic Exclusion Zones (EEZs) is needed. However, implementing a network of MPAs in Europe, and all the factors that need consideration within that (including climate change), is likely to be challenging because marine conservation governance approaches are often developed at both a European and national level (Metcalfe *et al.*, 2013).

Integrated marine environmental protection is challenged by a number of factors. There are substantial knowledge gaps regarding the condition of the seas and the effects of anthropogenic pressures. There is also a lack of coordination between community and international measures (including the coordination between neighbouring states), and it is widely acknowledged that conservation measures are often restricted in scope, therefore granting limited environmental protection (Maier and Markus, 2013; Hull, 2013).

Collaborative management (or co-management) is a commonly published concept that is employed by governments and local communities to manage and protect natural resources in partnership at a national level (Jones *et al.*, 2013; Fleming and Jones, 2012); however, there is little literature on how neighbouring nations, within Europe or globally, will manage adjoining marine areas now or in the future, particularly those habitats and species requiring protection. The European Commission (EC) argues that a regional approach (European level within this context) to a marine environmental protection regulatory system is required given that marine ecosystems are transboundary and cannot be adequately governed, managed and protected by separate and fragmented national jurisdictions (Maier and Markus, 2013). The EC states that *"…appropriate co-ordination and co-operation between countries bordering sea regions is required"* (Maier and Markus, 2013; COM, 2005/505).

It has been acknowledged that through the implementation of the MSFD, as the environmental pillar of the European Maritime Policy, enhanced cooperation between neighbouring states may hopefully develop (Calado *et al.*, 2010) and that integration of a cross-sectoral policy under this directive will strengthen marine protection (Salomon and Dross, 2013). However, Calado *et al.* (2010) and Hull (2013) also note that, despite this, different approaches to marine management are being implemented by the different OSPAR member states. Ireland, Iceland and Denmark are reported to have no immediate plans to implement a forward-looking Marine Spatial Plan; Norway, Spain and the UK are in the process of implementing marine planning using different approaches. Sweden has a marine spatial plan in place for territorial waters; and Germany and the Netherlands have published plans for their entire EEZs (Calado *et al.*, 2010). The difference in marine management strategies being applied within Europe leads to a number of questions, notably: will these management strategies be complementary? How will Priority Marine Habitats (PMHs) that straddle EEZ boundaries be managed? What happens if climate change leads to the movement of a PMH into an EEZ where it is currently not protected?

This chapter aims to investigate the management issues raised by species loss or movement over a transnational area such as the North Sea. The chapter will use the Maxent model tested in Chapter 4 to predict the changing distribution of 10 OSPAR habitat forming PMH species. The implications of the findings of the modelling will be discussed later in the chapter.

5.1.1 Aims and Objectives

- ***Research Overview:*** *The knowledge gained from this study will enable decision makers to examine the possible impact of a warming ocean on Priority Marine Habitats, and how collaborative management between countries and regions could be best implemented.*

  Key Tasks:
  - *Investigate how the distribution of the features change due to climate change*
  - *Investigate what the impacts or management requirements are for loss of the feature*
  - *Investigate what the Marine Planning boundary issues are that arise*
  - *Investigate how management will adapt if the feature moves*

A lack of data and shortcomings in the understanding of the potential impacts of climate change on the distribution of PMHs and their management have led to a requirement for the development of potential predictive management tools.

The aim of this study is to predict changes in the distribution and extent of the PMHs (Table 5.1) within the north east Atlantic under future scenarios of environmental change, through the application of a species distribution modelling method (Maxent) (Phillips and Dubik, 2008; Phillips *et al.*, 2006). The application of this modelling method for the prediction of PMH distribution was carried out in Chapter 4. In summary, the method mapped the potential future distribution of the PMH, *Modiolus modiolus* beds, within UK waters under increased ocean temperatures scenarios (2009 – 2100). This study will expand this method and apply it to the PMHs listed in Table 5.1. Further analysis techniques will be applied in order to determine the extent of "conservation hotspots" under baseline (2009) and projected scenarios (increased ocean temperatures by 2100); whether a movement of the PMHs can be predicted between member state boundaries; and what the implications of this may be for marine conservation and management.

In 2006 (Table 5.1), the OSPAR contracting parties submitted a summary of the distribution of listed habitats, Priority Marine Habitats (PMHs), within the OSPAR area (determined as ‘threatened and/or declining species and habitats’ under the OSPAR Convention for the Protection of the Marine Environment of the north-east Atlantic 1992). The data are being continuously updated as more surveys are undertaken, with the most recent submission and publication of data at time of writing defined as the 2012 dataset. The 2012 dataset incorporates any new discoveries of PMHs since the 2006 submission and also excludes any previously erroneous submissions. This study will utilise the 2012 dataset.

Table 5.1: Reported Priority Marine Habitats within OSPAR member states

	Deep-sea sponge aggregations	***Lophelia pertusa* reefs**	***Ostrea edulis* beds**	**Seapens & burrowing megafauna communities**	***Zostera* beds**	**Maerl beds**	***Modiolus modiolus* horse mussel beds**	***Sabellaria spinulosa* reefs**	**Intertidal *Mytilus edulis* beds on mixed and sandy sediments**	**Coral gardens**
Belgium	*x*	*x*	*Y* *Ex***	*x*	*x*	*x*	*x*	*x*	*x*	
Denmark	*x*	*Y***	*x*	*x*	*x* **	*x*	*x*	*x*	*x*	
France	**	*Y***	*P***	*P***	*P***	*P***	*P***	*P***	*P***	
Germany	*x*	*x*	*Ex*	*P***	*Y***	*x*	*x*	*P***	*Y***	
Iceland	*Y***	*Y***	*x*		*Y***	*Y***		*Y*	*Y***	
Ireland	*Y***	*Y***	*Y***	*Y***	*Y***	*Y***	**		*Y*	
Netherlands	*x*	*x*		*Y***	*P***	*x*	*x*	*x*	*P*	
Norway	*P***	*Y***	*P*	*Y***	*Y***	*P***	*P*	*x*	*P*	**
Portugal	*Y***	*Y***				*Y***				**
Spain	**	*Y***		*P***	*P*	*P*	*x*			**
Sweden	*x* **	*Y***	*P*	*Y***	*Y***	*P***	*P***	*x*	*P***	
UK	**	*Y***	*Y*	*Y***	*Y***	*Y***	*Y***	*Y***	*Y***	**
High seas	*Y*	*Y***	*x*		*x*	*x*	*x*	*x*	*x*	

Key:	***Y***	Data have been supplied for the listed habitat (not necessarily by the respective Contracting Party).
	x	The listed habitat has not been reported as being present in the Contracting Parties' waters or the high seas (either currently or in the past).
	P	The habitat has been reported as being present in the Contracting Parties' waters but no data have been supplied.
	Ex	The habitat has been reported as having occurred in the Contracting Parties' waters in the past but is now considered to be extinct.
	**	Presence data were reported in 2012

Source: Adapted from http://www.ospar.org

5.2 Methods

5.2.1 Priority Marine Habitats Presence Data

To ensure comparability with the study carried out in Chapter 4, Priority Marine Habitat occurrence records were extracted from the 2012 OSPAR priority habitats data (JNCC, 2012a) as per Chapter 4. As a result of the limited geographical coverage of some of the environmental layers prepared for the model, a number of records were excluded because they did not coincide with one of more of the environmental layers. The environmental layers were chosen based on their considered suitability to benthic PMHs. A criterion for this study was to use environmental layers that were freely and publically available, to demonstrate the cost effectiveness and applicability of this method. It is acknowledged that better environmental layers (in terms of spatial extent and geographic resolution) may be available, but the layers chosen herein were concluded as best representation of our selection criteria.

The mapped distributions of the PMHs within the 2012 OSPAR dataset are shown in Figures 2.1 to 2.11.

5.2.2 Environmental Data

Data on environmental variables relevant to the selected benthic marine habitats were obtained from publically available sources then assigned to a 0.05^{o} grid in ArcMap 10.1 Geographical Information System (GIS) software (0.05^{o} was selected as best representative resolution for the available environmental layers). Depth, slope, sea bottom temperature, sea bottom salinity, current speed and euphotic depth were identified as suitable environmental layers, as shown in Table 5.2. Seabed type or landscapes were not included because available layers had very limited geographic coverage.

The increased ocean temperature scenario outlined in Chapter 4 for the epoch 2100 was established for this study. Therefore a 4^{o}C increase in ocean bottom temperature was therefore assumed over the entire region (Figures 5.1 and 5.2).

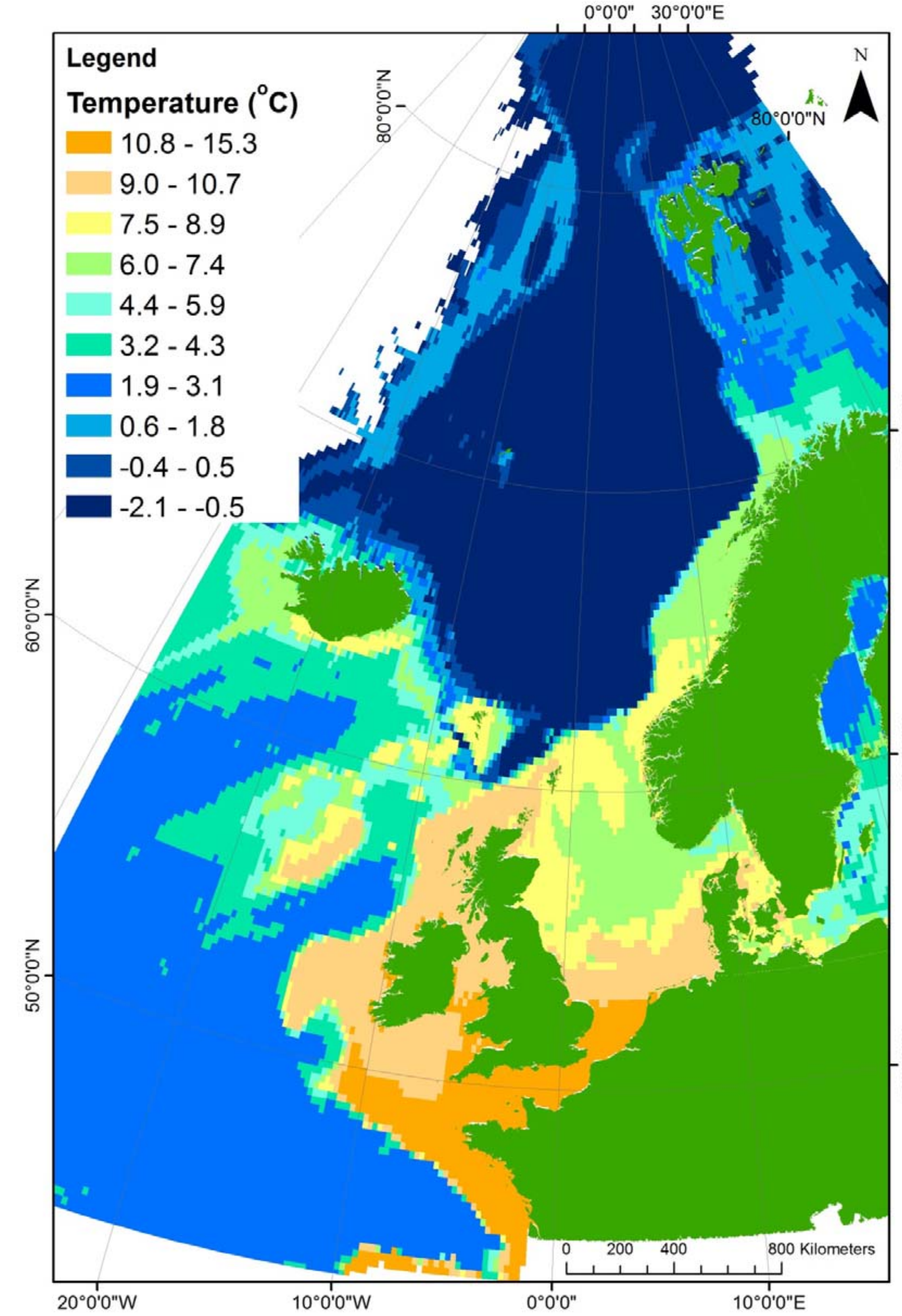


Figure 5.1: 2009 (Baseline) Sea Bottom Temperature across OSPAR study Region

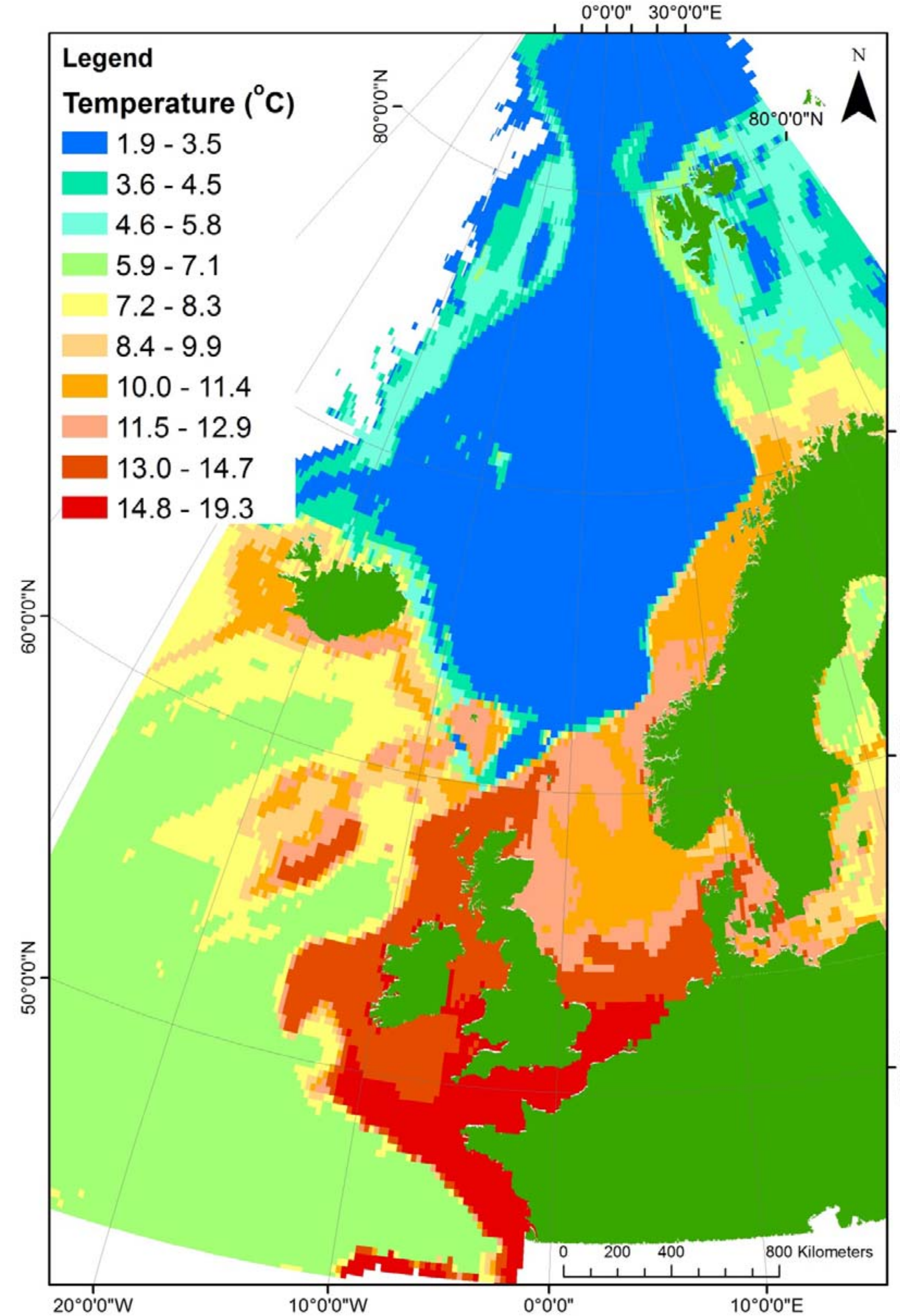


Figure 5.2: Projected 2100 Sea Bottom Temperature across OSPAR study Region

Table 5.2: Environmental variables and data sources

Variable	Source
Bathymetry: depth (m)	GEBCO_08 30-second arc Bathymetry resolution (GEBCO, 2011)
Slope: percentage gradient of the seafloor (%)	Adapted in ArcGIS 9.3 from: GEBCO_08 30-second arc Bathymetry resolution (GEBCO, 2011)
Sea Bottom Temperature: climatological annual mean sea bottom temperature (^{o}C). Adapted from NOAA depth interval data	NOAA World Ocean Atlas (Locarnini *et al.*, 2010)
Bottom Salinity: climatological annual mean sea bottom salinity (PSS). Adapted from NOAA depth interval data	NOAA World Ocean Atlas (Antonov *et al.*, 2010)
Current Speed: average spring current speed (ms^{-1})	(Lien *et al.*, in prep-b; Lien *et al.*, in prep-a)
Euphotic Depth: (m)	NASA Giovanni portal: http://disc.sci.gsfc.nasa.gov/giovanni

5.2.3 Species Distribution Model

Species distribution modelling and model validation/evaluation was carried out using the method described in Chapter 4; Section 4.2.5.

The probability of occurrence values (0 to 1) estimated in the Maxent model training and projection runs were separated into 3 categories:

iv.) 0.5 – 1.0 representing "most suitable" habitat;

v.) 0.1 - 0.49 representing "less suitable" habitat; and

vi.) 0.0 – 0.09 representing "unsuitable" habitat.

5.2.4 Conservation Management Hotspots

Economic Exclusion Zones and OSPAR Marine Regions

The "most suitable" habitat for each PMH was taken forward for further analysis. The area and percentage cover of each PMH's "most suitable" habitat category were calculated within each member state's EEZ for the baseline (2009) and the projected (2100) years. Given the extent of the available layers; Spain, Portugal and High Seas EEZs were excluded and not all countries' EEZs were completely covered by the environmental layers. The EEZs not completely covered within the model, the area of "most suitable" habitat coverage exported from the model was corrected based the actual extent of the full EEZ in order to remove error of under or over prediction.

Conservation Management Score

In order to determine where the most potential conservation management activities would be required, "most suitable" habitats model outputs for all PMHs were overlaid in ArcMap 10.1, with each PMH being given a value of 1. These values were then summed to give a conservation management score (i.e. the number of co-occurring PMHs; see Figures 5.3 and 5.4). The higher the summed value, the more potential PMHs occur in a particular region and the highest scores were considered ‘conservation management hotspots’.

Overlap Matrix

The "most suitable" habitat layers for each PMH were overlaid with each other individually and the area of overlap calculated (km^2). A matrix outlining the co-occurring PMHs in 2009 compared with 2100 was constructed.

Comparative data analysis was also carried out in order to determine whether the spatial grid/cell size of this study would have an influence on the conservation management hotspot score. The model was re-run for all PMHs under the same modelling conditions outlined above for Scottish waters only for a 0.005^{o} grid. The model outputs were exported to ArcMap 10.1 and analysed as before.

5.3 Results

5.3.1 Species Distribution Model

The Maxent model was trained using internally selected sub-sets within Maxent's automated validation test for each PMH. The training AUC values, shown in Table 5.3, ranged from 0.907 to 0.999 indicating excellent model prediction with little variation shown over the 10 replicates. The test AUC values ranged from 0.904 to 0.999 and showed only slightly more variation over the replicated runs.

A final model was run for each of the sampling scenarios using the full occurrence records. The AUC values for the final model for all PMHs ranged from 0.907 to 0.999 and generally equalled the average of the replicated models. The high AUC values, with low variability between and within training and testing replicate sets, indicate excellent model performance in terms of predicting habitat suitability.

Table 5.3: Threshold-independent area under the curve (AUC) indices for PMH model.

Priority Marine Habitat	10 Replicates (90/10) Model						Full Model
	Train			Test			AUC
	Average AUC	AUC		Average AUC	AUC		
Coral gardens	0.987	Min.	0.9866	0.984	Min.	0.9737	0.987
		Max.	0.9884		Max.	0.99	
Zostera beds	0.991	Min.	0.9906	0.988	Min.	0.981	0.991
		Max.	0.9917		Max.	0.9928	
Deep-sea sponge aggregations	0.96	Min.	0.974	0.947	Min.	0.8966	0.962
		Max.	0.9623		Max.	0.9722	
Intertidal *Mytilus edulis* beds on mixed and sandy sediments	0.996	Min.	0.996	0.996	Min.	0.9915	0.996
		Max.	0.9964		Max.	0.9978	
Lophelia pertusa reefs	0.944	Min.	0.9423	0.937	Min.	0.9102	0.944
		Max.	0.9453		Max.	0.9529	
Maerl beds	0.989	Min.	0.9888	0.986	Min.	0.9817	0.989
		Max.	0.9894		Max.	0.9914	
Modiolus modiolus horse mussel beds	0.993	Min.	39927	0.991	Min.	0.9937	0.993
		Max.	0.9934		Max.	0.986	
Ostrea edulis beds	0.999	Min.	0.9987	0.999	Min.	0.9965	0.999
		Max.	0.9995		Max.	1	
Sabellaria spinulosa reefs	0.991	Min.	0.9904	0.99	Min.	0.9853	0.991
		Max.	0.9911		Max.	0.9936	
Sea-pen and burrowing megafauna communities	0.907		0.9037	0.904		0.8977	0.907

The environmental variables with the highest and lowest gains are shown in Table 5.4. Highest gain indicates the most useful information by itself when determining the location of suitable habitat; and lowest gain indicates the variable with the most information not present in the other variables, when determining location of suitable habitat.

Overall, when bottom temperature was omitted the jack knife analysis showed the lowest gain for all PMHs except *Mytilus edulis* beds (euphotic depth), indicating that the bottom temperature variable (for all PMHs except *M. edulis* beds) has the most information not present in the other variables, when determining location of suitable habitat. The AUC values remained above 0.9 for each model run following omission of each environmental variable in turn; this indicates 'excellent' model performance. Bottom temperature was measured as contributing the most to the model for all PMHs except *M. edulis* beds (euphotic depth), *Sabellaria* reefs (euphotic depth) and deep sea sponge aggregations (slope). It is acknowledged that other environmental variables may change as a result of climate change (e.g. salinity, depth, velocity etc.), however other variables were not considered within this study owing to the general poor understanding of climate change scenarios in the marine environment, as discussed by Gormley *et al*. (2013).

Table 5.4: Jack knife test of variable importance: Highest and Lowest Gains

Priority Marine Habitat	Highest Gain	Lowest Gain
Coral gardens	Bathymetry	Bottom Temperature
***Zostera* beds**	Euphotic Depth	Bottom Temperature
Deep-sea sponge aggregations	Bathymetry	Bathymetry
Intertidal *Mytilus edulis* beds on mixed and sandy sediments	Euphotic Depth	Euphotic Depth
***Lophelia pertusa* reefs**	Bottom Temperature	Bottom Temperature
Maerl beds	Bottom Temperature	Bottom Temperature
***Modiolus modiolus* horse mussel beds**	Bottom Temperature	Bottom Temperature
***Ostrea edulis* beds**	Bottom Temperature	Bottom Temperature
***Sabellaria spinulosa* reefs**	Euphotic Depth	Bottom Temperature
Sea-pen and burrowing megafauna communities	Bottom Temperature	Bottom Temperature

5.3.2 Conservation Management Hotspots

Economic Exclusion Zones and OSPAR Marine Regions

The area of "most suitable" (MS) habitat within each member state's EEZ was calculated over the 2 epochs (2009 and 2100). The 2009 modelled test results were directly comparable with the training results, showing that the models generally predicted potential habitat presence in the same EEZs as the training model (Table 5.3). Due to the limited distribution of PMHs and minimal amount of presence records, it was not possible to use completely independent datasets for training and testing the model other than the 90/10% training/test datasets outlined in the methods. The full model was constructed using the full 2012 dataset. For *Modiolus* beds, *Sabellaria* reefs and *Mytilus* beds the model predicts a greater range than that reported to OSPAR in 2012. The least information has been submitted on coral gardens, indicating that this PMH may be under-studied. Table 5.5 shows results of the areas of PMH in 2009 and Table

5.6 shows the results of the projected model (2100) and indicates where potential habitat losses and gains may occur. In summary, the model predicts that the most significant loss of MS habitat will occur for *Lophelia pertusa* reefs, *Modiolus modiolus* beds, seapens and burrowing megafauna communities and *Mytilus edulis* beds. The most significant potential habitat gains are reported for *Ostrea edulis*, *Zostera* and maerl beds.

In addition, the number of potential "changes" (defined as loss or gain of most suitable habitat) is shown in Table 5.6 for the different EEZs. The results show that Iceland and Belgium may gain the most PMH habitats by 2100; while Germany may potentially lose the greatest amount of habitat. The habitat loss and gain per EEZ was mapped to clearly illustrate the countries where the most changes may occur (Figure 5.3). Spain, Portugal and the High Seas regions were outside the boundary of the environmental layers used in the model and therefore no results were available.

The change in the distribution of each modelled PMH was also calculated over the defined OSPAR Marine Regions, as well as the number of potential changes.

Table 5.7 shows that the Arctic waters are unlikely to lose any potential PMH MS habitat between 2009 and 2100, although the results only indicate a small increase (≤3%) in potential habitat. The Greater North Sea and Celtic Seas regions both lose 5 and gain 5 different potential PMH MS habitats by 2100, with the greatest gain noted for *Ostrea edulis* and Maerl beds. The loss of habitat for both regions is ≤2% of the whole of their region. The percentage calculations shown in Table 5.5 are weighted to account for the amount of each OSPAR Marine Region covered within the model.

Results in Table 5.7 and Figure 5.4 indicate that the Celtic Seas and the Greater North Sea regions face the same amount of loss and gain; this is also reflected between the number of changes illustrated in Figure 5.3 for the UK and Ireland EEZs. Overall, a net gain of potential PMH “hotspots” is observed throughout Europe.

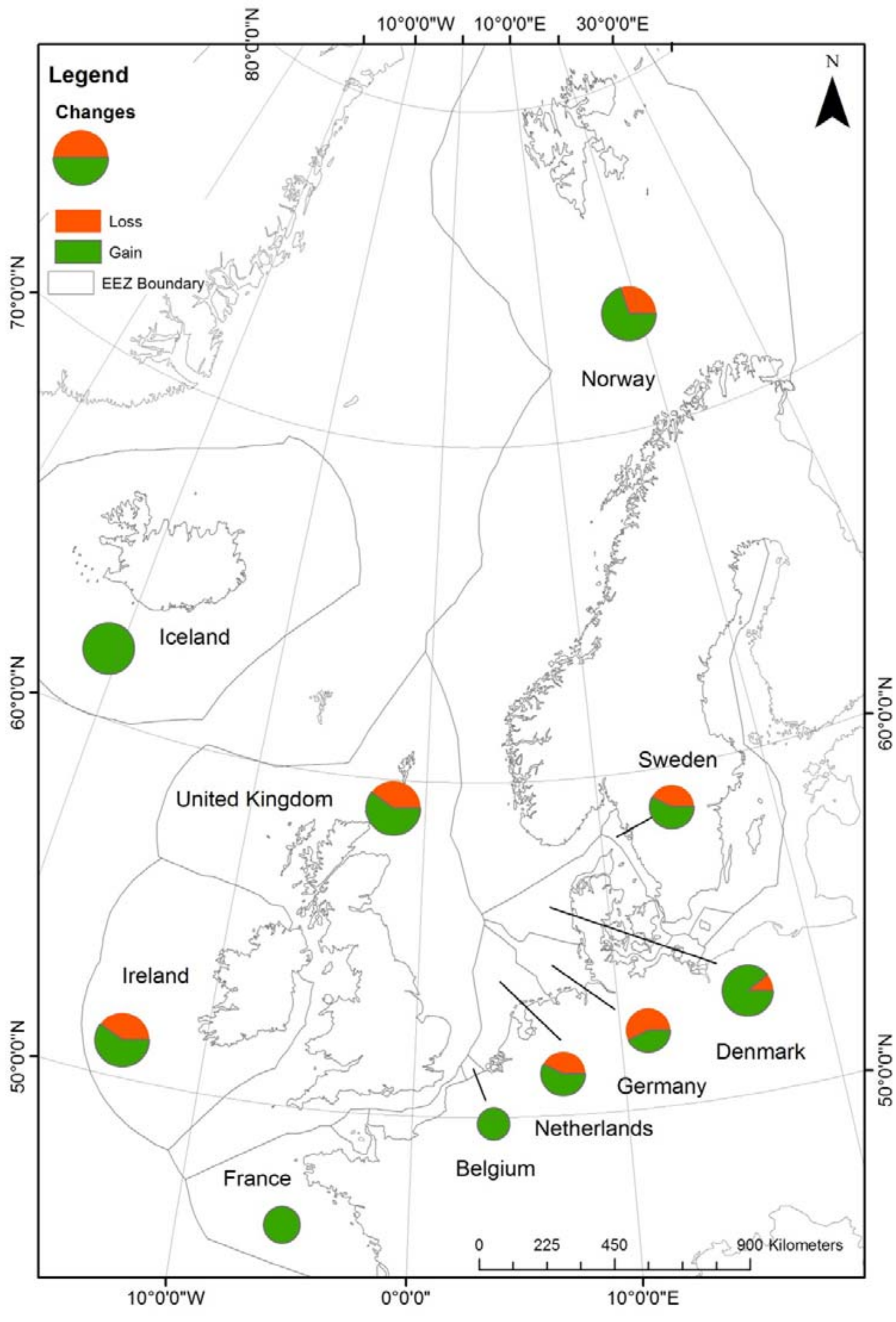


Figure 5.3 : Loss and gain of PMH "hotspots" per EEZ. Size of chart varied by total no. changes

Table 5.5: Area of "Most Suitable" Habitat, 2009 per OSPAR Country Exclusive Economic Zone

EEZ	Area of EEZ (km^2)	Area of MPAs (km^2)	% EEZ Protected	Area of "Most Suitable" Habitat (km^2) 2009									
				Deep-sea sponge aggregations	*Lophelia pertusa* reefs	*Ostrea edulis* beds	Seapens & burrowing megafauna communities	*Zostera* beds	Maerl beds	*Modiolus modiolus* horse mussel beds	*Sabellaria spinulosa* reefs	Intertidal *Mytilus edulis* beds on mixed and sandy sediments	Coral gardens
Belgium	3,480	0	0	0*	0*	1,103*	0*	271	0*	0*	987	0*	0†
Denmark	103,178	12,512	12	0*	1,668*	0*	4,715	2,995*	734	586	1,050	291	0†
France	327,609	4,581	1	0	0	4,665*	0	5,013*	5,221*	0	1,255*	0	0†
Germany	56,658	16,912	30	0*	0*	0*	9,187*	2,028*	0*	678	5,413*	3,115*	0†
Iceland	777,641	81	0.01	18,311*	21,345*	0*	8,383†	1,009*	368*	0*	0†	29	2,768†
Ireland	419,787	4,238	1	27,006*	15,334*	423*	29,853*	3,071*	1,340*	6,543*	1,765	172	12,721†
Netherlands	61,855	8,366	14	0*	0*	2,449†	1,114*	3,386*	0*	2,344	3,181	1,568	0†
Norway	1,745,561	80,877	5	1,429*	101,044*	0*	19,494*	7,276*	5,474*	0*	16	128	1,572*
Portugal	1,955,682	6,709	0.3	-	-	-	-	-	-	-	-	-	-
Spain	557,462	2,504	0.4	-	-	-	-	-	-	-	-	-	-
Sweden	159,380	1,264	1	0*	1,543*	0*	1,598*	786*	375*	0	11	0	0†
UK	761,408	53,544	7	57,719*	56,549*	6,949	142,608*	11,988*	5,520*	33,881*	16,700*	1,946*	28,796*
High seas	-	330,927	-	-	-	-	-	-	-	-	-	-	-

Key:
- * Model results match data reported to OSPAR in 2012
- (grey shading) Model results do not match data reported to OSPAR in 2012
- † No data provided in 2012

Table 5.6: Change in "Most Suitable" habitat area within the north-east Atlantic economic exclusion zones (OSPAR member states) between 2009 and 2100

EEZ	Area of EEZ	Area of MPAs	% EEZ Protected	Area of "Most Suitable" Habitat (km^2) 2100										No. Losses	No. of Gains	Total No. of Changes
				Deep-sea sponge aggregations	Lophelia pertusa reefs	Ostrea edulis beds	Seapens & burrowing megafauna communities	Zostera beds	Maerl beds	Modiolus modiolus horse mussel beds	Sabellaria spinulosa reefs	Intertidal Mytilus edulis beds on mixed and sandy sediments	Coral gardens			
Belgium	3,480	0	0	0	0	3,008	0	929	2,255	0	1,026	0	0	0	4	4
Denmark	103,178	12,512	12	0	724	34,811	674	12,225	23,049	0	530	0	33	5	4	9
France	327,609	4,581	1	103	0	46,122	0	8,628	22,927	0	1,453	0	0	0	5	5
Germany	56,658	16,912	30	0	0	35,378	0	5,890	21,647	0	3,247	0	0	4	3	7
Iceland	777,641	81	0.01	63,633	30,427	223	13,717	2,946	2,304	243	588	29	18,945	0	9	9
Ireland	419,787	4,238	1	46,009	2,949	114,354	1,616	7,028	16,087	0	1,928	0	27,808	4	6	10
Netherlands	61,855	8,366	14	0	0	41,443	0	7,121	35,455	0	4,336	0	0	3	4	7
Norway	1,745,561	80,877	5	26,107	89,574	1,947	18,491	12,843	12,677	1,140	372	50	21,051	3	7	10
Portugal	1,955,682	6,709	0.34	-	-	-	-	-	-	-	-	-	-	-	-	-
Spain	557,462	2,504	0.45	-	-	-	-	-	-	-	-	-	-	-	-	-
Sweden	159,380	1,264	1	0	537	2,524	980	2,070	3,533	0	0	0	33	3	4	7
UK	761,408	53,544	7	98,710	8,643	245,947	15,706	34,884	121,845	0	16,739	0	52,386	4	6	10
High seas	-	330,927	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Key:		Habitat **loss** between 2009 and 2100		Habitat **gain** between 2009 and 2100		**No change** between 2009 and 2100

Table 5.7: Change in "Most Suitable" habitat area within the OSPAR Marine Regions

OSPAR Marine Regions	Area of Region (km^2)	Change in "Most Suitable" Habitat (Weighted Percentage) between 2009 and 2100											No. Loses	No. Gains	Total No. Changes
		% of Region covered by model	Deep-sea sponge aggregations	*Lophelia pertusa* reefs	*Ostrea edulis* beds	Seapens & burrowing megafauna communities	*Zostera* beds	Maerl beds	*Modiolus modiolus* horse mussel beds	*Sabellaria spinulosa* reefs	Intertidal *Mytilus edulis* beds on mixed and sandy sediments	Coral gardens			
Arctic Waters	5,777,807	61	3	3	0.01	1	0.3	0.2	0.02	0.01	0	1	0	10	10
Greater North Sea	777,441	93	1	1	29	2	7	22	0.04	3	0	1	5	5	10
Celtic Seas	378,904	73	2	0.1	56	0	6	18	0	1	0	0.03	5	5	10
Wider Atlantic	7,151,794	14	4	0.3	0.4	0.4	0	0	0	0	0	3	1	4	5
Bay of Biscay and Iberian Coast	539,153	0	-	-	-	-	-	-	-	-	-	-	-	-	-

Key:		Habitat **loss**		Habitat **gain**		**No change**

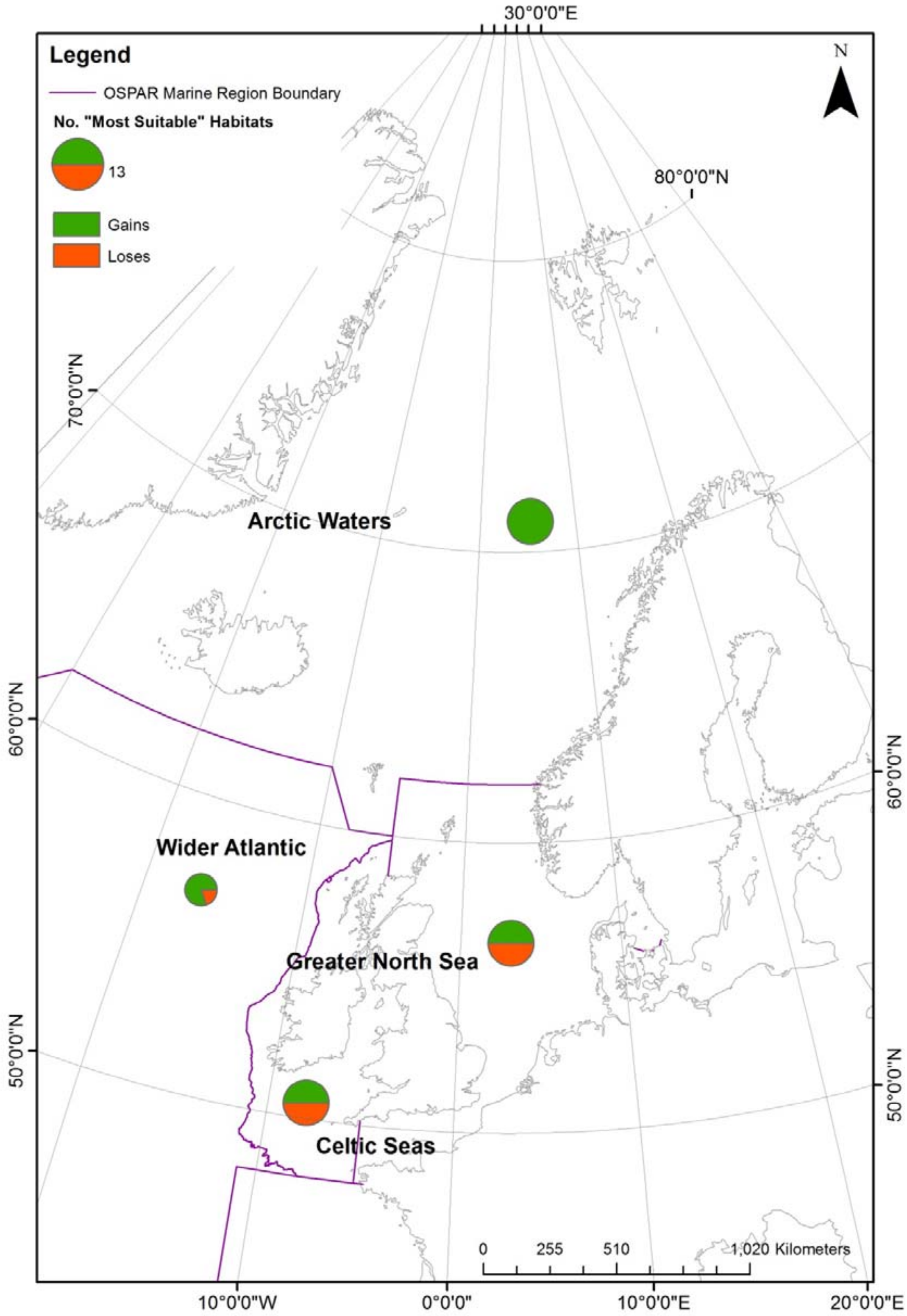


Figure 5.4 : Loss and gain of PMH "hotspots" per OSPAR marine region. Size of chart varied by total no. changes

Overlap Matrix

The area cover (km^2) of "most suitable" habitat was calculated for 2009 and 2100 and the percentage overlap of each PMH was calculated. The percentage overlaps are shown in the Matrix in Figure 5.5. The matrix illustrates that there is a greater amount of low percentage (>0 to 15%) overlap in 2100 compared with 2009; but a greater proportion of high percentage (>20%) overlap in 2009 compared with 2100. Table 5.8 summarises the overlaps based on the percentage level.

The percentage overlap of Coral and Sponges remains the same between 2009 and 2100.

		2009									
		Coral	Lophelia	Maerl	Modiolus	Mytilus	Ostrea	Sabellaria	Sponge	Zostera	Seapens
2100	Coral	Coral	13	0	0	0	0	0	29	0.01	0.1
	Lophelia	6	Lophelia	0.1	0.2	0.01	0	0	20	1	1
	Maerl	0.01	0.01	Maerl	6	0	9	0.4	0	24	0.3
	Modiolus	0	0.02	0.00003	Modiolus	0.00001	0	0.0003	0	0.001	0.001
	Mytilus	0	0	0	1	Mytilus	0.0003	0.001	0	0.001	0
	Ostrea	0.1	0.000001	0.0027	0	0	Ostrea	0.0019	0	0.001	0
	Sabellaria	0	0.000001	0.0004	0.2	0.3	5	Sabellaria	0	0.001	0.000002
	Sponge	29	5	0.000002	0	0	2	0	Sponge	0	0.00001
	Zostera	0.04	0.05	0.0021	1	0.04	12	15	0.1	Zostera	0.00001
	Seapens	4	1	0.000007	0.2	0.02	0.00001	0.03	2	0.2	Seapens

Key:		>20% overlap		10-19% overlap		1-9% overlap		>0-1% overlap		No overlap

Figure 5.5: Percentage overlap between PMFs in 2009 and 2100

Table 5.8: Summary of co-occurring PMFs in 2009 compared to 2100

<table>
<tr><th colspan="3">Percentage overlap</th></tr>
<tr><th>>20%</th><th>10-19%</th><th>>0-1%</th></tr>
<tr><th colspan="3">2009</th></tr>
<tr><td>Coral and Sponge</td><td rowspan="3">Coral and Lophelia</td><td>Maerl and Ostrea</td></tr>
<tr><td>Lophelia and Sponge</td><td>Lophelia and Zostera</td></tr>
<tr><td>Maerl and Zostera</td><td>Lophelia and Seapens</td></tr>
<tr><th colspan="3">2100</th></tr>
<tr><td rowspan="9">Coral and Sponge</td><td rowspan="4">Zostera and Ostrea</td><td>Coral and Lophelia</td></tr>
<tr><td>Coral and Seapens</td></tr>
<tr><td>Lophelia and sponge</td></tr>
<tr><td>Lophelia and Seapens</td></tr>
<tr><td rowspan="5">Zostera and Saballeria</td><td>Modiolus and Mytilus</td></tr>
<tr><td>Modiolus and zostera</td></tr>
<tr><td>Ostrea and Sabellaria</td></tr>
<tr><td>Ostrea and Sponge</td></tr>
<tr><td>Sponge and Seapens</td></tr>
</table>

Results for the comparative Scotland-only model indicated that in 2009 the majority of the co-occurring PMHs (84%) were the same when compared to European wide model; with only a small difference (16%) observed between the PMHs outlined in Table 5.9.

Table 5.9: Co-occurring Priority Marine Habitats – European vs. Scotland model

Overlapping PMH	Overlap Observed	
	European Model	Scotland Model
Coral vs. Zostera	Yes (<0.1%)	No
Coral vs. Seapens	Yes (<0.1%)	No
Lophelia vs. Mytilus	Yes (<0.01%)	No
Maerl vs. Mytilus	No	Yes
Modiolus vs. Sponge	No	Yes
Mytlius vs. Seapens	No	Yes
Sponge vs. Seapens	Yes (<0.001%)	No

Conservation Management Score

The area of co-occurring MS habitats was calculated in ArcMap 10.1 for both 2009 and 2100. The areas and percentage cover of MS habitat for 2009 and 2100 are shown in

Tables 5.10 and 5.11 respectively; and areas of loss or gain between 2009 and 2100 are highlighted.

The 2009 results showed that there was a maximum of 4 co-occurring MS PMHs, which only occurred in the French and UK EEZs. Three co-occurring MS PMHs occurred in all EEZs except Sweden; and all EEZs contained 2 or fewer overlapping PMHs. The largest area of no co-occurring PMHs (Conservation Management Score = 0) occurred in the Netherlands.

The results for 2100 (Table 5.10) are colour coded to illustrate where there is a loss or gain in the percentage cover of co-occurring PMH "most suitable" habitat. Results indicate that in 2100 there will generally be an increase in co-occurring PMH habitat across all EEZs. Areas of only 0 or 1 PMH habitat decrease in line with the increasing areas of co-occurring PMHs.

Figure 5.6 and Figure 5.7 illustrate the change in overlapping PMHs between 2009 and 2100. These figures show the biggest observed differences occur in Belgium, France, Germany and the Netherlands. The "Conservation Management Hotspots" in the UK, Norway and Sweden remaining relatively unchanged. The countries have been put in geographic order and the graphs generally show that there is the potential for an increase in conservation hotspots in the countries at lower latitudes.

The modelled conservation hotspots are mapped in Figures 5.8 (2009) and 5.9 (2100).

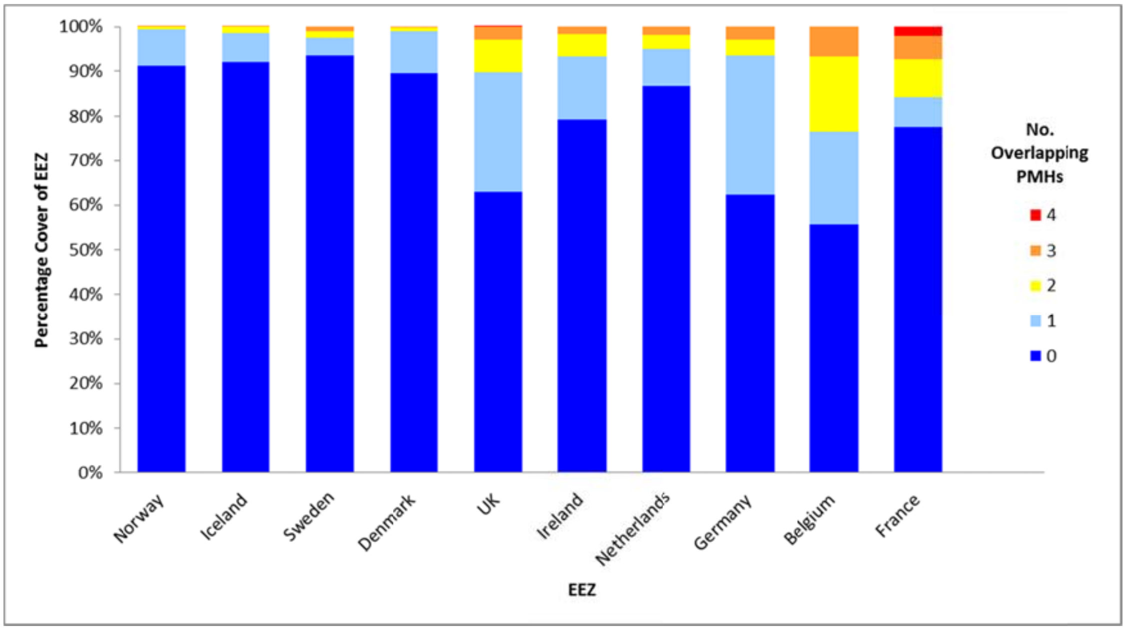


Figure 5.6: Percentage cover of co-occurring PMHs per country EEZ - 2009

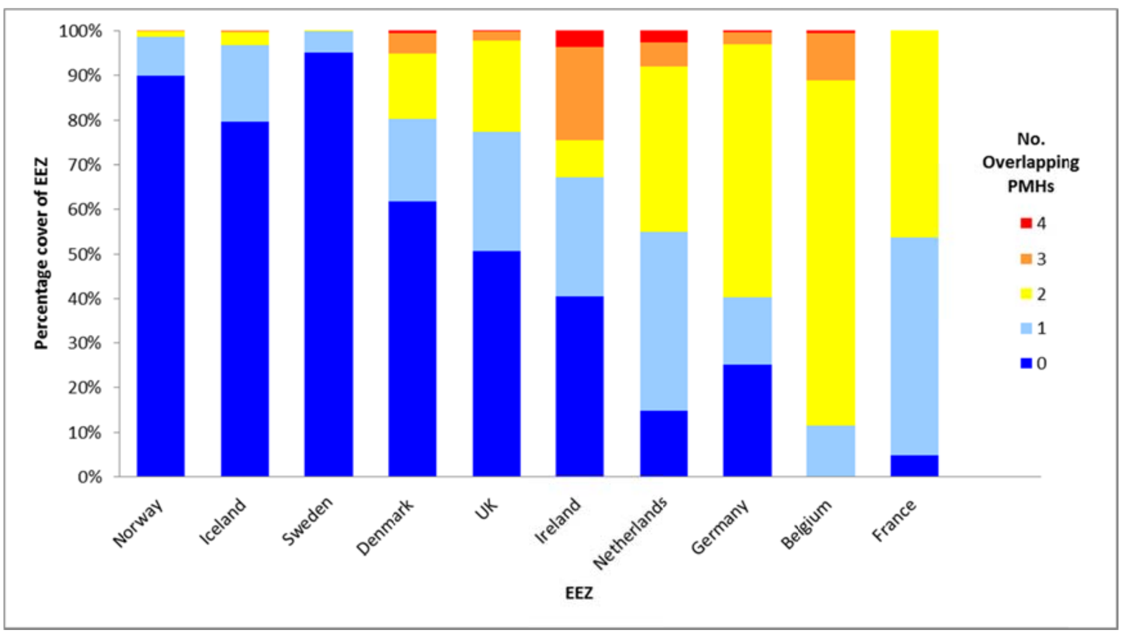


Figure 5.7: Percentage cover of co-occurring PMHs per country EEZ - 2100

Table 5.10: Area of conservation "hotspots" within the north-east Atlantic economic exclusion zones (OSPAR member states) in 2009

2009	Area of EEZ (Km^2)	Area of MPAs (Km^2)	% EEZ Protected	Hotspot Ranking (0 to 4) - Area (Sq km)					Total Area (Km^2)	% of EEZ covered in model	Hotspot Ranking (0 to 4) - Percentage (weighted)				
				0 (no PMFs)	1	2	3	4 (4 PMFs co-occur)			0 (no PMFs)	1	2	3	4 (4 PMFs co-occur)
Belgium	3,480	0	0	1601	597	485	190	0	2873	83	46	17	14	5	0
Denmark	103,178	12,512	12	67064	7039	647	92	0	74842	73	65	7	1	0.09	0
France	327,609	4,581	1	26929	2375	2902	1761	753	34720	11	8	1	1	1	0.23
Germany	56,658	16,912	30	23098	11541	1373	1053	0	37065	65	41	20	2	2	0
Iceland	777,641	81	0.01	482317	34463	7276	369	0	524425	67	62	4	1	0.05	0
Ireland	419,787	4,238	1	247431	43965	15213	5352	0	311961	74	59	10	4	1	0
Netherlands	61,855	8,366	14	51730	4756	1984	1046	0	59516	96	84	8	3	2	0
Norway	1,745,561	80,877	5	1285468	115802	6788	246	0	1408304	81	74	7	0.39	0.01	0
Sweden	159,380	1,264	1	60450	3009	163	0	0	63622	40	38	2	0.1	0	0
UK	761,408	53,544	7	423695	179544	50054	18484	513	672290	88	56	24	7	2	0.07

Table 5.11: Area and percentage change in conservation "hotspots" within the north-east Atlantic economic exclusion zones (OSPAR member states) between 2009 and 2100

2100	Area of EEZ (Km^2)	Area of MPAs (Km^2)	% EEZ Protected	Hotspot Ranking (0 to 4) - Area (Sq km)					Total Area (Km^2)	% of EEZ covered in model	Hotspot Ranking (0 to 4) - Percentage (weighted)				
				0 (no PMFs)	**1**	**2**	**3**	**4 (4 PMFs co-occur)**			**0 (no PMFs)**	**1**	**2**	**3**	**4 (4 PMFs co-occur)**
Belgium	3,480	0	0	0	270	1807	692	121	2890	83	0	8	52	20	3
Denmark	103,178	12,512	12	44923	13384	10545	5183	31	74066	72	44	13	10	5	0.03
France	327,609	4,581	1	1366	13553	12920	5149	961	33949	10	0.42	4	4	2	0.29
Germany	56,658	16,912	30	8533	5107	19119	4007	237	37003	65	15	9	34	7	0.42
Iceland	777,641	81	0.01	411661	88498	15119	1655	0	516933	66	53	11	2	0.21	0
Ireland	419,787	4,238	1	162668	106705	33198	6808	987	310366	74	39	25	8	2	0.24
Netherlands	61,855	8,366	14	8899	23594	21853	3279	1546	59171	96	14	38	35	5	2
Norway	1,745,561	80,877	5	1207060	116665	16103	2562	40	1342430	77	69	7	1	0.15	0
Sweden	159,380	1,264	1	58074	2367	983	621	0	62045	39	36	1	1	0.39	0
UK	761,408	53,544	7	329781	172962	132795	24712	3364	663614	87	43	23	17	3	0.44

Key:		Habitat **loss** between 2009 and 2100		Habitat **gain** between 2009 and 2100		**No change** between 2009 and 2100

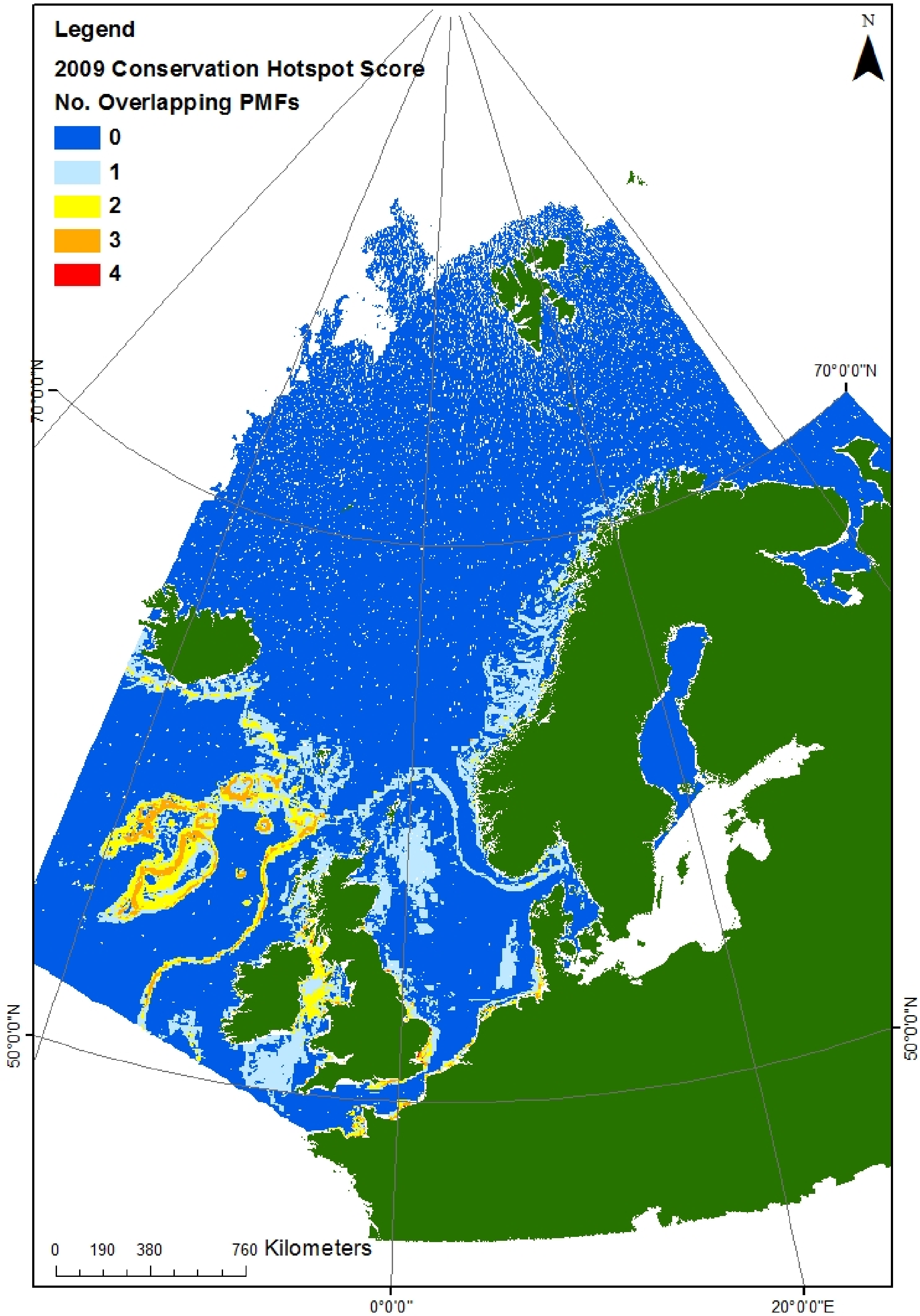


Figure 5.8: Modelled OSPAR conservation "hotspots" 2009

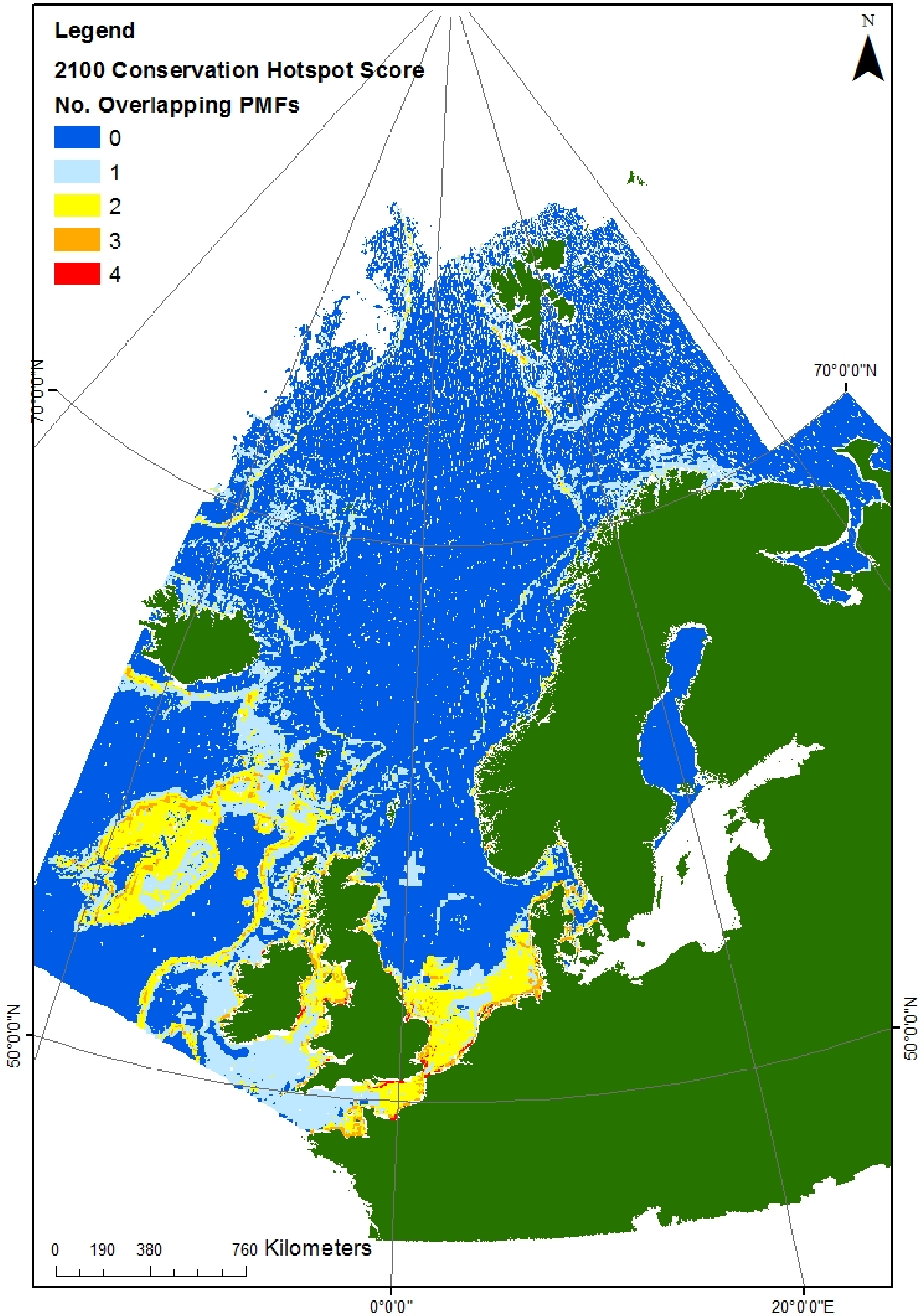


Figure 5.9: Modelled OSPAR conservation "hotspots" 2100

5.4 Discussion

The aim of this study was to examine the extent of potentially suitable areas for PMHs throughout the OSPAR region (NE Atlantic); calculate the potential losses and gains of habitats per EEZ and OSPAR Marine Region between 2009 and 2100; and to examine the implications for national and international marine spatial planning.

Overall there is the potential for a movement and/or increase in the extent of some PMH in northern Europe under an increased ocean temperature scenario (4^{o}C) by 2100 (IPCC, 2007; Gormley *et al.*, 2013); furthermore, countries will need to adapt to these changes.

5.4.1 Species Distribution Model and Climate Change

The Maxent Species Distribution Model used in this study has been widely applied in both marine (Jones *et al.*, 2012; Ross and Howell, 2012; Reiss *et al.*, 2011; Ready *et al.*, 2010; Gormley *et al.*, 2013) and terrestrial environments (Pearson and Dawson, 2003; del Barrio *et al.*, 2006; Carvalho *et al.*, 2011; Rose and Burton, 2009; Nativi *et al.*, 2009; Dawson *et al.*, 2011), and has generally been considered to be robust in the context of marine management (Ross and Howell, 2012). Within the present study the trained baseline model provided a good overall prediction in relation to all modelled PMHs.

Specific limitations with the use of this model in this particular study include the lack of robust, continuous environmental data covering the whole geographic region; the overall potential lack of historic distribution data (for declined habitats); and the lack of environmental layers that may be useful for the distribution of benthic habitats e.g. seabed landscapes. All seabed type or landscape layers (e.g. EUSeaMap or Mareano datasets); only covered a very limited area of some EEZs; therefore it was not possible to include these layers in the final model.

With regard to input data availability; taking oyster beds (*Ostrea edulis*) as an example; the potential extent of these beds in Europe are largely unknown due to historic harvesting of the resource, although there is evidence that they were widespread e.g. (Olsen, 1883). From the model, the distribution of the current ecological niche is far greater in the modelled study area than is occupied in the present day and hind casting of the historic distribution of oyster beds is therefore unlikely to be accurately represented in this model due to the small quantity of input data. However, projected results for the expanse of the oyster bed range by 2100 indicate an opportunity for widespread oyster bed restoration over the next 100 years or so, potentially facilitated by the protection of conservation management hotspots; areas where the oyster bed ecological niche is overlapped by other PMH; or through a collaborative or systematic management strategy.

In addition, the model may be over-predicting the range of *Modiolus* beds, *Sabellaria* reefs and *Mytilus* beds under the 2100 projection scenario. However, with regard to data availability and accuracy; insufficient survey effort may have been applied to these PMHs or data reported to OSPAR for these PMHs is poor, or erroneous. Another factor for these particular PMHs may be that the habitat has in fact decreased between the 2006 and 2012 reporting, one of the reasons these habitats are considered PMHs in the first place.

Integrating the concept of climate change into policy and management is understandably complicated, and without the use of predictive models, relatively difficult. In fact, the impacts of climate change are still perceived to be distant and are generally ignored in developing day-to-day ocean management strategies (Ruckelshaus *et al.*, 2013).

It is acknowledged that the scale and pace of change in European and national policy presents a number of challenges in managing the marine environment, and places considerable demand on the marine community to work together to provide the information necessary to fulfil set objectives (Rees *et al.*, 2013), especially given that the European marine territory is larger than its land territory; and a considerable effort is therefore essential to fulfil all the legislative requirements (Zampoukas *et al.*, 2013). Zampoukas *et al*. (2013) reported that many institutions throughout Europe are involved in monitoring strategies which would be greatly improved (cost, effectiveness and efficiency) from better coordination, not to mention providing more robust and coherent management for the marine environment. However, this statement may also cause issues of its own. For example, the introduction of new or altered methods may lead to the creation of a new baseline dataset if methods of measure or measures used are non-comparable; therefore leading to wasted effort and money and a baseline that is not representative. Decision makers need access to sound scientific evidence that is targeted to their needs in order to achieve sustainable use and protection of the marine environment (Rees *et al.*, 2013) now and probably in the future.

5.4.2 Conservation Management Score

Myers *et al.* (2000) acknowledged that a good approach to conservation is to identify "hotspots", or areas featuring exceptional concentrations of endemic species and experiencing exceptional loss of habitat. This study has identified areas within the north-east Atlantic, where potential PMH hotspots could occur now and in the future.

Further model development would be required in order to ascertain whether the distribution of certain PMHs is in any way interdependent, for example, if the retreat or loss of one species resulted in the subsequent retreat or loss in another.

Comparing the European wide model to a Scotland only model showed that there was minimal difference between the overlapping PMHs at difference spatial cell/grid scale. It is understandable that the Scotland model is more sensitive than the wider European model due to the resolution of the environmental layers used, but it provides a level of confidence within the European model. In addition, the Scotland model included a Landscape layer which was not available for the European model; and the European model included a euphotic depth layer, which was too coarse a resolution to be included in the Scotland model. The models were re-run excluding the landscape and euphotic depth layers with the results indicating that overlapping PMHs were the same (excluding Oyster beds and *Sabellaria* reefs); however, model predictions based on these layers were considered too wide, and the inclusion of the landscape and/or the euphotic depth were deemed necessary in order to refine the model predictions. No data were available on the distribution of oyster beds or *Sabellaria* reefs in the Scotland model as the 2012 occurrence records for these PMHs fell out with the Scottish sea area.

This comparative analysis showed that there is a general pattern of which PMHs may co-occur (regardless of which environmental layers are included in the model). In particular, it would be expected that the deep sea PMHs and shallower PMHs would co-occur respectively. It is possible that the model is over predicting areas of most suitable habitat where shallow water and deep water PMHs co-occur, or depth is not the actual limiting factor for these PMHs. The model would be further refined at all spatial scales if full environmental layer datasets were more readily available.

5.4.3 Co-ordinating Management

Systematic conservation planning is described by Metcalfe *et al.* (2013) as a process that combines short-term assessment (identifying priority areas for conservation management) together with a long-term management framework – essentially the process of locating, implementing and maintaining areas that are managed to promote the persistence of biodiversity and other natural values (Micheli *et al.*, 2013) such as the sustainable exploitation of marine resources. However, in practice, conservation planning is rarely systematic and "Ad hoc" conservation has resulted in the conservation and management of areas that do not best represent regional biodiversity; with boundaries and management strategies that are often governed by political or economic constraints (Micheli *et al.*, 2013).

Although the results from this study indicate that the same number of changes occur within the Greater North Sea, Celtic Seas and Arctic Waters Marine Regions (Table 5.5); and UK, Norway and Ireland (Figure 5.3), different management prioritisation is implicated. In the Arctic region, for example, it will become increasingly necessary to develop protective spatial management measures such as MPAs if the recommendations and aspirations of the OSPAR agreement are to be met. In contrast, extant and developing MPA networks in the Greater North Sea and Celtic Seas cannot “maintain” PMHs indefinitely and the locations and objectives of MPAs will have to accommodate some flexibility over time. Collaborative management will be of particular significance in the Greater North Sea region due to the number of bordering countries. Management initiatives and strategies will need to be put in place in order to manage the potential loss and gain of PMHs between regions. For example, a European wide working group for marine conservation or environmental protection would allow for collaborative management strategies to be discussed, agreed and initiated; potentially through the involvement of boundary agreements for managed retreat/expansion of PMHs where necessary.

In addition, management at a national (EEZ) or regional (OSPAR or Europe) level will also need to be considered. The results presented here indicate a potential for the greatest increase in higher ranked conservation hotspots to occur at lower latitudes and that some nations (e.g. Belgium) have a greater role to play in the future than they do at present. This issue of managed retreat (loss or gain of PMHs) also links into Descriptor 2 of the MSFD, non-indigenous species. Managed retreat of PMHs under a climate change scenario may lead to their replacement by non-indigenous species. However, if this is accounted for within future collaborative strategies, may not actually represent a management weakness, and may be considered acceptable with the appropriate management agreed.

5.4.4 Habitat Loss, Fragmentation and Stepping Stones

Habitat loss and fragmentation together pose one of the most serious threats to global biodiversity because restricted gene flow between populations combined with limited dispersal ability, can intensify the isolation by distance effect and play an important role in determining population viability within a degraded landscape (Ezard and Travis, 2006). Population responses to fragmentation are as much to do with the pattern of habitat loss as they are to do with the total amount destroyed (Ezard and Travis, 2006). Connectivity of PMHs and MPAs containing them is therefore of paramount importance. A PMH that becomes disconnected may be able to persist for a certain length of time, but may become susceptible to damage or disease if recruitment is not maintained. Understanding the gene flow of a population is one way of measuring connectivity and contributes to knowledge of which sites are important to one another.

However, this is an area with identified research and knowledge gaps. The creation of, for example, a "toolbox" of genetic markers would provide for underlying knowledge of PMH species and provide the first step to identifying priority connectivity corridors and provide knowledge for the potential development of habitat restoration methods. Investigation into the use of genetic marker on PMHs was carried out in Chapter 7 of this thesis (See Chapter 7 for full details and results).

Management strategies and plans in some countries could also account for the potential creation of stepping stone habitat during the development of, for example, offshore wind farms. The artificial reefs could obviously provide additional settlement habitat for reef forming species, and therefore provide more habitat for other benthic species and fish; potentially providing *de-facto* MPAs. However, on the other hand, these stepping stone habitats may lead to the increased rapidity with which non-native invasive species spread.

5.5 Conclusions

This study has shown that the boundary management of biodiversity hotspots will need to be considered within the assessment of GES under the MSFD throughout Europe; and the co-operation between member states and marine regions needs to be enhanced in order to provide a robust adaptive management strategy going forward. At present, marine management strategies are principally concerned with managing the status-quo, essentially maintaining or enhancing habitats in one location. Marine Spatial Planning needs to include a horizon that actually manages for the future with specific set conservation targets and monitoring; and which does not simply state that climate change will be accepted.

5.6 Chapter 5 Summary

- there is the potential for countries and regions to both lose and gain PMHs between 2009 and 2100
- Overall, there is a net gain in PMH “hotspots” across Europe
- Countries that may not be considered to be "big players" from a marine conservation perspective at present will need to consider the possibility of playing a bigger role in the future to ensure adequate protection
- Managing "biodiversity hotspots" will be just as important as managing the species or habitats individually
- Policy managers could use this study to help devise future conservation and management strategies, for examples collaborative plans and research, such as habitat restoration, risk mitigation and managed migration.

Chapter 6. Marine Protected Area Management Effort

6.1 Introduction

It is acknowledged that substantial knowledge gaps exist regarding the condition of the sea and the effect of anthropogenic pressures on the marine environment (Maier and Markus, 2013; Giakoumi *et al.*, 2012); and the rules that are currently in place covering marine environmental conservation mainly target specific problems in certain sectors or policy areas, and are not specifically aimed at marine conservation (Maier and Markus, 2013).

To date, no official assessment of the cumulative impacts of anthropogenic pressures on the marine environment has been made in any European sea, despite the tight implementation schedule of the Marine Strategy Framework Directive (MSFD) (Korpinen *et al.*, 2012; Halpern *et al.*, 2008); but the interest in the compatibility of ocean uses and the management of cumulative impacts on the marine environment is increasing with the move towards ecosystem-based marine spatial planning (Moreno *et al.*, 2012; Day *et al.*, 2008; Gilliland and Laffoley, 2008; Halpern *et al.*, 2008; Giakoumi *et al.*, 2012).

The development of Marine Spatial Planning (MSP) and a Marine Protected Areas (MPA) network involves an understanding of where conservation protection will be most appropriate. For example, areas of high conservation importance that are already impacted by human activities may not be the best representation of a "pristine" habitat or represent Good Environmental Status (GES) under the Marine Strategy Framework Directive (MSFD); nor be suitable for exclusive protection if the human activities are considered to be socio-economically important. Surveying entire marine regions (at a country level) to identify potential MPAs is impractical on both a cost and time basis. Therefore, suitable strategies need to be developed in order to whittle down the expanse of marine environment to create a more focussed approach to marine conservation designations.

The management of multi-use Marine Protected Areas can be complex and the potential costs (both monetary and time) associated with this management can be significant, requiring careful and sometimes time consuming planning and consideration. Balmford *et al.* (2004) reported that annual running costs per unit area of an MPA were higher in MPAs that were smaller, closer to coasts, and in high-cost, developed countries. In another study by Ban *et al.* (2011) modelled scenarios indicated that a single large no-take reserve is less expensive to manage than a multiple-use MPA of the same area with a 30% no-take component. The literature on MPA management tends to focus on the management of stakeholders (Himes, 2007; Pomeroy and Douvere, 2008), the direct financial costs of MPAs (Ban *et al.*, 2011; McCrea-Strub *et al.*, 2011; Balmford *et al.*, 2004) or, the prediction of management effectiveness in terms of the MPA success (Angulo-Valdés and Hatcher, 2013; Pomeroy *et al.*, 2005; Alder *et al.*, 2002).

6.1.1 Aims and Objectives

- ***Research Overview:*** *This chapter will utilise data and methods outlined in previous chapters to carry out two assessments for MPA network management. Data and tools developed within this study will provide evidence which will enable better selection of future management and planning options.*

  Key Tasks:

  - *Investigate how the management effort requirement of sensitive environmental features can be predicted*

This study will focus on two separate aspects of the assessment of potential influences of human activities on conservation "hotspots" in Scottish waters. First, an assessment will be carried out on where potential areas of conflict may occur between conservation and anthropogenic activities (Pressure-Ecosystem Analysis) and include an assessment of the MPA Marine Regions (Marine Region Assessment; MRA). Following that, an assessment will be made to determine whether it is possible to predict the level of management effort required for conservation areas (Prediction Indicators).

Korpinen *et al*. (2012) and Moreno *et al*. (2012) introduce methods for the assessment of the spatial distribution of human activities in the Baltic Sea (Korpinen *et al.*, 2012) and Spanish marine waters (Moreno *et al.*, 2012) in relation to the MSFD. These methods specifically examine the distribution and magnitude of human activities at sea, their associated pressures (Korpinen *et al.*, 2012; Moreno *et al.*, 2012) and their potential impacts on the marine ecosystem (Korpinen *et al.*, 2012).

This study aims to expand on these methods and introduce the concept of identifying areas where anthropogenic pressures may overlap with areas of "conservation hotspots" within Scottish waters. Conservation hotspots within this study are classified as areas of benthic habitat forming Priority Marine Features (PMFs) or Priority Marine Habitats as defined by OSPAR (OSPAR Commission, 2004)) and as outlined in Chapter 2. This study will not include the specific impact assessment (through co-efficient weighting) of the human activities (see McWhinne *et al.*, 2013). Instead, it will act as the first steps towards identifying areas where the highest and lowest number of activities may occur in relation to areas of high or low conservation importance. Essentially identifying areas where conservation protection may be most significantly applied; and areas where conservation protection may not be applicable, feasible or manageable.

An assessment of pressures and impacts on the marine environment is one of the key features of the MSFD (DEFRA, 2011d); with the requirement to implement measures to achieve GES by 2020. GES means seas which are ecologically diverse and dynamic; are clean, healthy and productive within their intrinsic conditions, and use of marine resources are conducted at a sustainable level; thus safeguarding the potential for use by current and future generations (Korpinen *et al.*, 2012).

This study is, to our knowledge, one of the first spatial assessments of cumulative human activites and conservation hotspots in Scottish waters; and should be considered as a first step towards more comprehensive impact assessments and plans under the MSFD.

The second part of this study proposes to test the null hypothesis that the level of management complexity (MC = the measure of the number of human activities occurring in an MPA simultaneously) within an MPA will not have a significant relationship to the MPA's management effort (i.e. number of casework events). Casework is defined as any work or statutory consultation associated with an MPA (e.g. planning applications, discharges or new fisheries). In addition, the study proposes to test the null hypotheses that management effort would not increase a) as the number of qualifying features within the MPA increased; b) with increased proximity to the coastline (e.g. offshore vs. inshore) (Balmford *et al.*, 2004); and c) if more 'publically appealing' features occurred within the MPA.

The second part of this study we will examine the level of Management Complexity within the currently designated MPAs in Scottish waters and through modelling and statistical analysis will determine which variables play an important role in defining the level of management effort required for each MPA. The analysis will subsequently be applied to the proposed MPAs (pMPAs) to ascertain if a prediction can be made to establish which MPAs may require the most management effort going forward.

The aim of this study is to develop a suitable indicator to predict how challenging or time-consuming the management of MPAs in Scottish waters might be.

6.2 Methods

6.2.1 Data Preparation

Priority Marine Features (PMFs) are habitats and species which are considered to be of marine nature conservation priority in Scottish waters (SNH, 2011b) and in this study only the PMF habitats formed by benthic habitat forming species were used. This study included: Coral gardens, *Zostera* beds, Deep-sea sponge aggregations, Intertidal *Mytilus edulis* beds on mixed and sandy sediments, *Lophelia pertusa* reefs, Maerl beds, *Modiolus modiolus* horse mussel beds and Sea-pen and burrowing megafauna communities. Insufficient data were available to justify the inclusion of *Ostrea edulis* beds and *Saberllaria spinulosa* reefs because records of these PMFs fell outside of the environmental layers used in this model.

In this study we utilised both actual surveyed distribution data for PMFs and modelled distribution data showing potential "Most Suitable" PMF habitat. PMF occurrence records were extracted from the 2012 OSPAR priority habitats dataset (JNCC, 2012a). The OSPAR records were imported into ArcMap 10.1 and buffered by 1km to represent the extent of the PMF. The PMFs were given a score of 1 and the number of co-occurring PMFs was summed (PMF Score).

In order to provide an assessment of areas that may be able to support PMFs and to predict PMFs outside the distribution and extent already reported (OSPAR 2012 dataset) Species Distribution Models (SDMs) were used. It was deemed appropriate to provide an assessment of modelled distribution of PMFs to account for areas that may not have been surveyed in full, in addition to the validation of the predictor indicators. The non-buffered records for each PMF were exported from ArcMap and run in the selected Species Distribution Model, Maxent (Phillips *et al.*, 2006). This combination of modelling techniques (Maxent) has previously been used in Chapter 4 and by Ross and Howell (2012) to determine the extent of a habitat forming species. The method tested in Chapter 4 is adapted for use in this study.

Environmental data used in Maxent were obtained from a number of online sources and converted in ArcMap 10.1 Geographical Information System (GIS) Software and assigned to a 0.005^{o} grid. The layers included: bathymetry, landscape, salinity, slope, seabed temperature and current velocity as outlined in Table 6.1. The layers were set to the extent of the Scottish waters (200nm outer seaward limit).

Following the method outlined in Chapter 4, the probability of occurrence values (0 to 1) estimated in the Maxent model were separated into the three habitat suitability categories (see Chapter 4; Section 5.2.3):

i.) 0.5 – 1.0 representing “most suitable habitat”;
ii.) 0.1 - 0.49 representing “less suitable habitat”; and
iii.) 0.0 – 0.09 representing “unsuitable” habitat.

The model was run for each PMF and the potential distribution of "Most Suitable" (MS) habitat was exported and mapped in ArcMap 10.1. The model predictions were tested using the ‘Area under the Curve’ (AUC) produced by Maxent. The data were randomly split into 90% training/10% test datasets using the option in Maxent for internal random test setting and cross validation for 10 replicate runs. Ten thousand randomly chosen pseudo-absence/background points were run for the whole study area.

The Maxent outputs were imported in ArcMap and the MS habitat areas for each PMF were extrapolated (as outlined above) and given a score of 1. These scores were again summed, (Most Suitable (MS) Habitat score).

All human activities (licensed activities) that occur in Scottish waters were collected following McWhinnie *et al* (2013) and imported into ArcMap 9.3. The data sources are outlined in Table 6.1. The human activities were given a score of 1 and summed to represent the extent of management complexity (Management Complexity (MC) score).

Table 6.1: Environmental and human activity data sources

Environmental Data	Source
Bathymetry: depth (m)	GEBCO_08 30-second arc Bathymetry resolution (GEBCO, 2011)
Slope: percentage gradient of the seafloor (%)	Adapted in ArcGIS 9.3 from: GEBCO_08 30-second arc Bathymetry resolution (GEBCO, 2011)
Sea Bottom Temperature: climatological annual mean sea bottom temperature (^{o}C). Adapted from NOAA depth interval data	NOAA World Ocean Atlas (Locarnini *et al.*, 2010)
Bottom Salinity: climatological annual mean sea bottom salinity (PSS). Adapted from NOAA depth interval data	NOAA World Ocean Atlas (Antonov *et al.*, 2010)
Landscape: seabed landscape features [Broad patterns in seabed character, such as seabed morphology determined by major geological and hydrographic processes]	UKSeaMap/MESH webGIS (Connor *et al.*, 2006) http://www.searchmesh.net/ ("Marine Landscapes" layer on interactive map)
Current Speed: average spring current speed (ms^{-1})	Atlas of UK marine renewable energy resources (DTI, 2004) Supplemented by: Current speed data on UKHO Navigation Charts (Marine Digimap, 2012) and BODC oceanographic data (BODC, 1998)

Table 6.1 (continued): Environmental and human activity data sources

Human Activities	Source
Archaeology (wrecks): Designated Shipwrecks and Marine Archaeological Sites	RCAHMS, Historic Scotland
Aquaculture (Lease Sites): Finfish and Shellfish (Active) Sites	The Crown Estate
Carbon Dioxide Storage (Storage Sites): Hydrocarbon Fields and Saline Aquifers	DECC
Dredging and Disposal (Regulated Areas): Dredged areas under license and Dumping grounds	Marine Science Scotland, EDINA
Military Activities (Restricted Areas): Firing Danger Areas, Submarine Areas and Practice Areas	EDINA
Nature Conservation (Protected Areas): SPAs, SACs, SSSIs, World Heritage Sites, National Nature Reserves, Ramsar Sites with a Marine Component	Scottish Natural Heritage
Oil and Gas (Regulated Areas): Significant Discoveries and Oil and Gas Seabed Wells. Fallowing Blocks, Hydrocarbon Fields and Oil and Gas areas under license.	DECC, EDINA
Ports, Harbours and Shipping (Transportation Areas): Harbour Jurisdictions, Shipping and Ferry Routes, Small Craft Facilities, IMO Traffic Scheme, Deep Water Route and Caution Areas	Maritime and Coastguard Agency, Department of Transport, RYA, via EDINA and Marine Scotland Science
Renewables (Lease Sites): Wind Farm Lease Sites, Tidal Lease Sites, Wave Lease Sites and Scottish Energy Awards	The Crown Estate
Sea Fisheries (Regulated Areas): Lamlash No Take Zone, Inshore Fisheries Group, Mackerel and Cod Nursery Grounds	CEFAS, Marine Science Scotland
Submarine Pipelines and Cables (Spatial Extent): Cables (Coaxial, Fibre optic and telegraph) and Pipelines	UK Deal via EDINA

Source: adapted from McWhinnie *et al*. (2013) and Chapter 4

6.2.2 Pressure-Ecosystem Analysis

The two PMF data sets (actual data and modelled data); and the human activities data set were assigned to a 3km x 3km grid and each cell was allocated the maximum hotspot score from each scale. The data sets were used in the original format for the Marine Region assessment analysis (i.e. not in gridded format) (see Section 6.2.3) and the Prediction Indicator Analysis (Section 6.2.4).

The pressure scores for the human activities and the conservation hotspots were separated into four categories as shown in Table 6.2.

Table 6.2: Pressure scores of Pressure-Ecosystem Analysis

Human Activities	PMF Hotspots	Most Suitable (MS) Hotspots
0 to 1 activities = Low pressure	0 PMFs = none	0 PMFs = none
2 to 3 activities = medium pressure	1 PMF = low PMH biodiversity	1 to 2 PMF = low PMF biodiversity
4 to 5 activities = high pressure	2 PMFs = medium PMF biodiversity	3 to 4 PMF = medium PMF biodiversity
6 to 7 activities = very high pressure	3 PMFs = high PMF biodiversity	5 PMFs = high PMF biodiversity

The data were mapped and displayed to analyse the points set out below.

1. The human activities dataset was overlaid and unionised with the MS Hotspot data set. Data were selected in order to map the following:
    a. Areas of Lowest Pressure vs. the areas of potential PMF biodiversity (for each category; Table 2)
    b. Areas of Highest Pressure vs. the areas of potential PMF biodiversity (Low to High only)
2. The PMF Hotspot dataset and OSPAR MPA data layer (OSPAR Commission, 2013) were overlaid and unionised with the potential PMF hotspot dataset. Data were selected in order to map the following:
    a. Areas of PMF biodiversity that overlap with the potential PMF hotspot areas were excluded to determine areas of potential PMFs not already known/reported
    b. Areas of MPAs already designated were excluded from the potential PMF hotspot layer
3. The PMF Hotspot dataset and the High to Very High pressures; and Low pressure layers were overlaid in order to map the following:
    a. Areas of PMFs already reported that are subject to very high or high pressure from human activities, therefore potentially not representing a "pristine" habitat
    b. Areas of PMFs already reported that are subjected to Low pressure from human activities, therefore potentially representing a "pristine" habitat

6.2.3 Marine Region Assessment

The area of the PMF Hotspots and human activities was calculated (km^2) within each of the 12 Scottish marine regions, in ArcMap 10.1, as designated by Marine Scotland (http://www.scotland.gov.uk/Publications/2012/12/3193). The calculated areas relate to the actual mapped distribution of Most Suitable habitat overlaps and not the 3km x 3km grid.

6.2.4 Prediction Indicators

The currently designated MPAs and proposed MPAs (pMPAs) were mapped in ArcMap 10.1 against the Human Activity, PMF and MS Hotspot scores to determine the extent of human activities and, reported and potential PMFs within each MPA. The data were exported to Excel and the area of each score in the MPAs was calculated.

In order to test the null hypothesis and to determine which variables, as outlined in Table 6.3, within a designated MPA provide the most information for the prediction of management time/effort of proposed MPAs (pMPAs), two Prediction Indicator methods were developed. Prediction Indicator 1 was based on ranking the pMPAs against the statistically significant correlations between the different variables. Prediction Indicator 2 was developed to provide a formula to calculate an approximate (average, maximum and minimum) number of caseworks required for each pMPA based on the linear regression relationship of the variables.

The variables considered within this study are outlined in Table 6.3. Where only qualitative data were available, a suitable numerical score was applied in order to create quantitative data suitable for statistical testing (Table 6.3). The MC, PMF and MS scores were extrapolated from the scores reported previously by the formulae in Table 6.3.

Table 6.3: Variable Scoring

<table>
<tr><th>Variable</th><th>Details</th><th colspan="4">Applied Numerical Scoring (if applicable)</th></tr>
<tr><td>Area</td><td colspan="5">Area of MPA calculated in ArcMap 10.1 (Km^2)</td></tr>
<tr><td>Location</td><td>Determined whether MPA falls within 12nm (inshore) or 200nm (offshore) Scottish boundaries</td><td>Offshore = 2</td><td>Inshore = 1</td><td colspan="2">Offshore and Inshore = 1.5</td></tr>
<tr><td>Type of feature</td><td>Type of qualifying features within MPA. Obtained from SNH SiteLink</td><td>Mammals (otter, seal, cetacean) = 2</td><td>Benthic Habitat (reefs, mudflats, sandbanks) = 1</td><td>Other = 0.5</td><td>Birds = 0.1</td></tr>
<tr><td>No. of features in MPA</td><td colspan="5">Number of qualifying features within MPA. Obtained from SNH SiteLink</td></tr>
<tr><td>Level of Management</td><td colspan="5">Number of casework events recorded for each MPA obtained from SNH SiteLink. Casework is defined as any work or statutory consultation associated with an MPA (e.g. planning applications , discharges or new fisheries)
SNHi - Information Service SiteLink (http://gateway.snh.gov.uk/sitelink/index.jsp)</td></tr>
<tr><td>MC Score</td><td colspan="5">Number of co-occuring human activities
Formula applied: MC Score = ∑(Area of MC Hotspots * MC Hotspot score)/Area of MPA</td></tr>
<tr><td>PMF Score</td><td colspan="5">Number of co-occurring PMFs
Formula applied: PMF Score = ∑(Area of PMF Hotspots * PMF Hotspot score)/Area of MPA</td></tr>
<tr><td>MS Score</td><td colspan="5">Number of co-occuring "most suitable" habitats
Formula applied: MS Score = ∑(Area of MS Hotspots * MS Hotspot score)/Area of MPA</td></tr>
</table>

To determine the relationship between the variables outlined in Table 6.3 at each MPA; Spearman's bivariate correlation coefficients were calculated using SPSS v 20.0. Variables with a significant correlation were defined as our indicators (Prediction Indicator 1). The prediction indicators were then used to calculate the management effort of pMPAs.

The analysis was re-run to determine whether a correlation could be recorded within varying distances (1km, 5km and 10km) from the MPA. The variables and scoring were calculated as before and the statistical analysis repeated.

The pMPAs were mapped against the available variables as above (excluding no. features, type features and number casework events as no data is currently available) in ArcMap 10.1 and the data was exported into Excel. The scores of each indicator for each pMPA were ranked in order of significance.

The variables were then tested for non-parametric normal distribution in SPSS and the linear regression relationship between the number of casework events and each of the variables was calculated for the variables showing normal distribution. Variables showing a significant linear regression relationship were taken forward to use in the predictive calculation (Prediction Indicator 2) for the number of casework events for the pMPAs. The following formulae were applied:

No. casework (inshore) = ($mv * v$ + c ($\pm r^2$))/L

Where:

mv (model variable) =	56.161	22.716	-63.138
v (variable) =	PMF Score	MS Score	MC Score
c (constant) =	38.017	34.699	89.812
L (location) =	As before (see Table 6.3)		

Given that many of the offshore located MPAs reported no caseworks, it was necessary to provide a correction for the MC Score as reflected in the following formula to compensate for the zero in the original calculation:

No. of casework events (offshore) = ($mv * (L - v)$ + c ($\pm r^2$))/ L

6.3 Results

6.3.1 Species Distribution Model

The training and test AUC values for each PMF are shown in Table 6.4. The average training and test AUC values range from 0.881 to 0.997 with very little variation across the replicated runs, indicating good to excellent model performance.

Table 6.4: Threshold-independent area under the curve (AUC) indices

Priority Marine Habitat	Average AUC	
	Training	Test
Coral gardens	0.953	0.928
Zostera beds	0.994	0.995
Deep-sea sponge aggregations	0.933	0.903
Intertidal *Mytilus edulis* beds on mixed and sandy sediments	0.998	0.997
Lophelia pertusa reefs	0.916	0.881
Maerl beds	0.987	0.985
Modiolus modiolus horse mussel beds	0.989	0.985
Sea-pen and burrowing megafauna communities	0.899	0.898

6.3.2 Pressure-Ecosystem Analysis

The "most suitable" habitat output (probability ≥0.5; potential PMF hotspots) from Maxent and the previously reported distributions of PMFs were mapped and assigned to the 3km x 3km grid. The distribution maps are shown in Figures 6.1 and 6.2. The maps illustrate where areas of reported PMF (Figure 6.1) and potential PMFs (Figure 6.2) co-occur, representing PMF and potential PMF biodiversity hotspots respectively.

The reported PMF distribution map (Figure 6.1) shows that there are areas where up to three PMFs may co-occur per 3km grid cell; with areas of highest PMF biodiversity primarily located along the west coast of Scotland. Although one area of high PMF biodiversity is located further offshore to the west of Scotland.

The modelled potential PMF map (Figure 6.2) illustrates that there are areas where there is the potential for up to 5 co-occurring PMF to occur. The results also indicate areas of higher potential PMF biodiversity primarily occur on the west coast of Scotland, but with some additional areas appearing on the east coast.

The human activity data were imported into ArcMap and assigned to the 3km x 3km grid. The results in Figure 6.3 show that there are up to 7 activities occurring in each cell, with the majority of Very High pressure occurring at limited locations along the west coast of Scotland. Low activity areas dominate the offshore region.

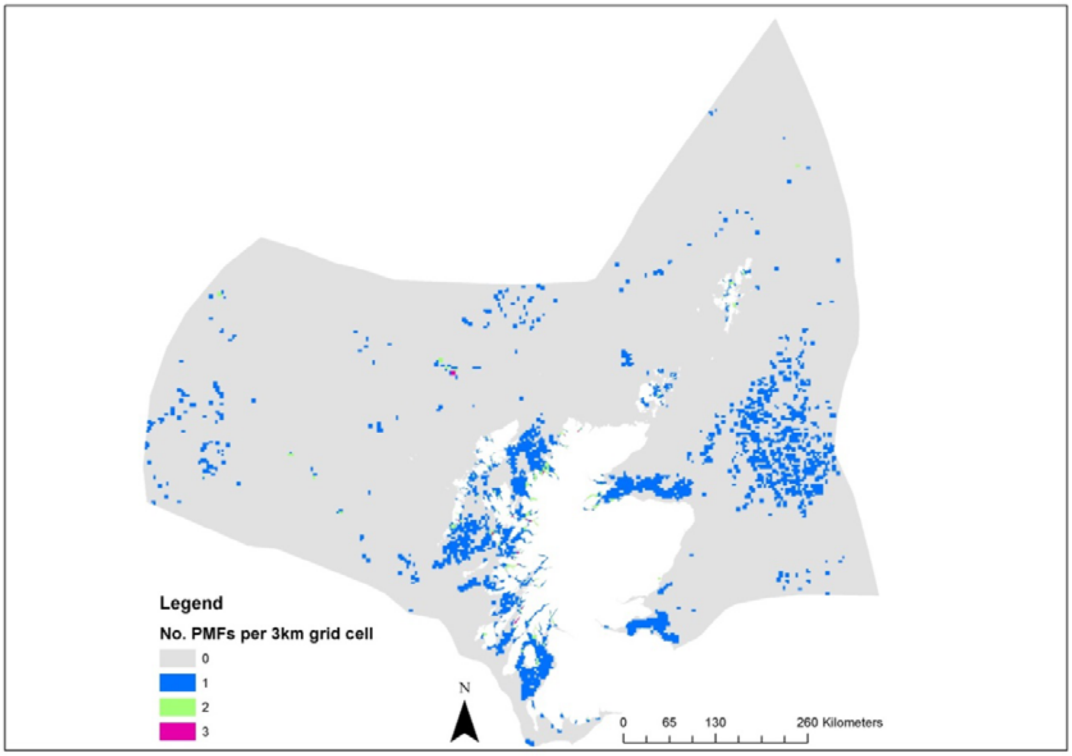


Figure 6.1: Number of Co-occurring Priority Marine Features

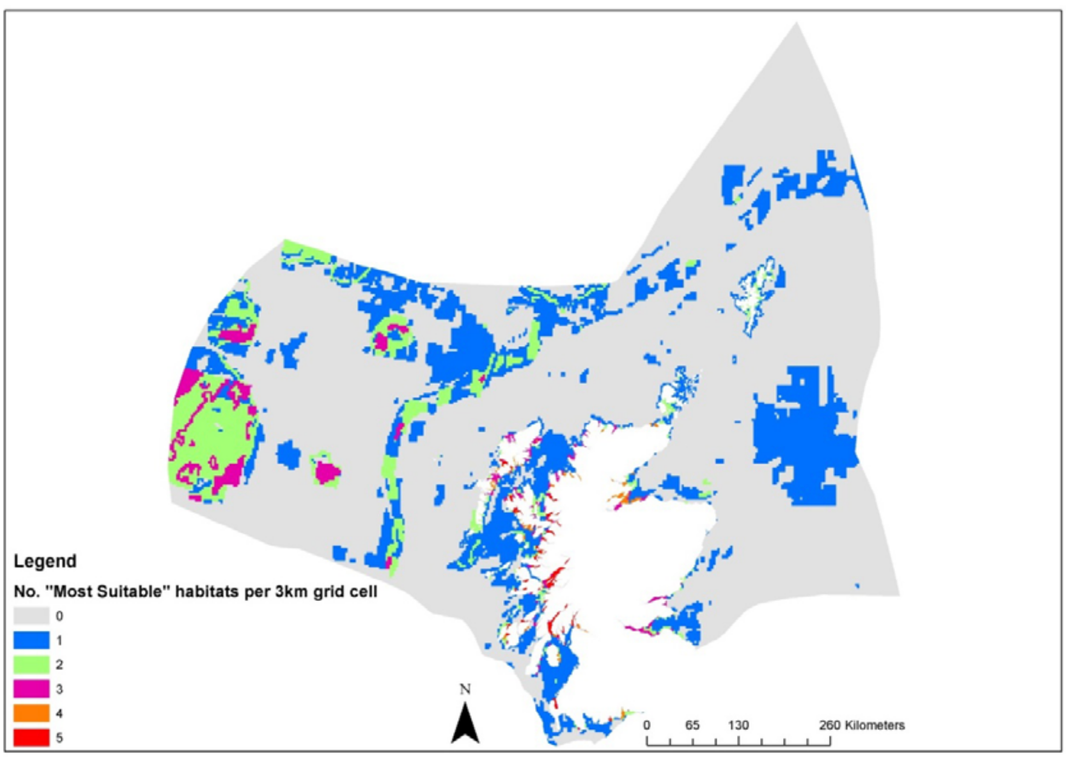


Figure 6.2: Number of Co-occurring Most Suitable Priority Marine Feature Habitat

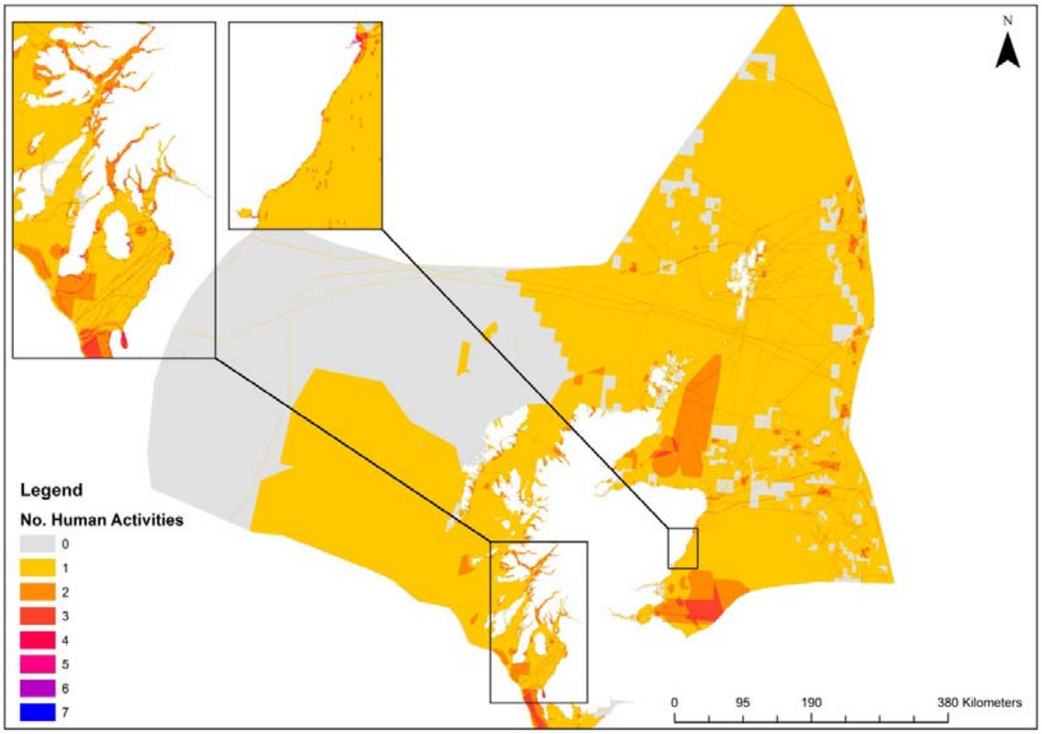


Figure 6.3: Number of Co-occurring Human Activities

Areas of Lowest Pressure

The areas of low pressure were extracted from the human activates layer and overlaid with the areas of potential PMF biodiversity (low, medium and high). The results were mapped and are illustrated in Figures 6.4 and 6.5.

Figure 6.4 shows areas of low pressure vs. high potential PMF biodiversity. The results show that areas are restricted in distribution and are solely located along the west coast of Scotland, representing a total of area of 154 km^2.

Figure 6.5 shows areas of low pressure vs. medium and low potential PMF biodiversity. Results show a wider distribution with areas represented along the east and west coasts, and offshore. The low pressure vs. medium potential PMF biodiversity area totals 8,267 km^2. This represents 2% of the Scottish sea area. A total area of 94,308 km^2 for low pressure vs. low potential PMF biodiversity is reported, representing 20% of the Scottish sea area.

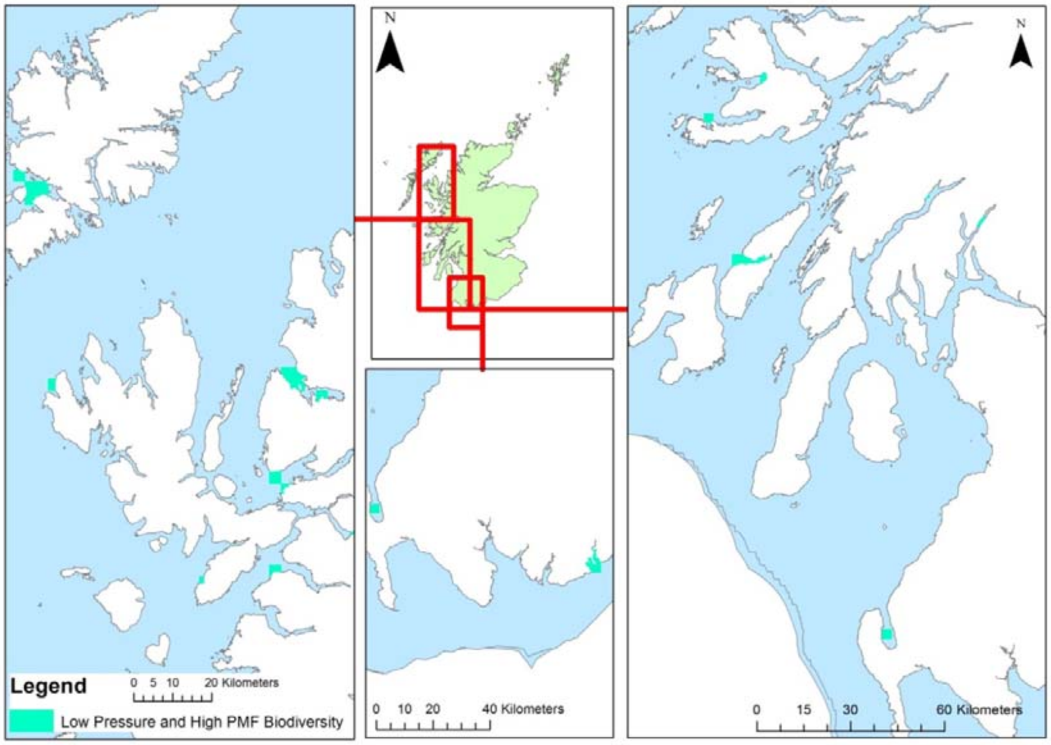


Figure 6.4: Areas of Low Pressure and High PMF Biodiversity

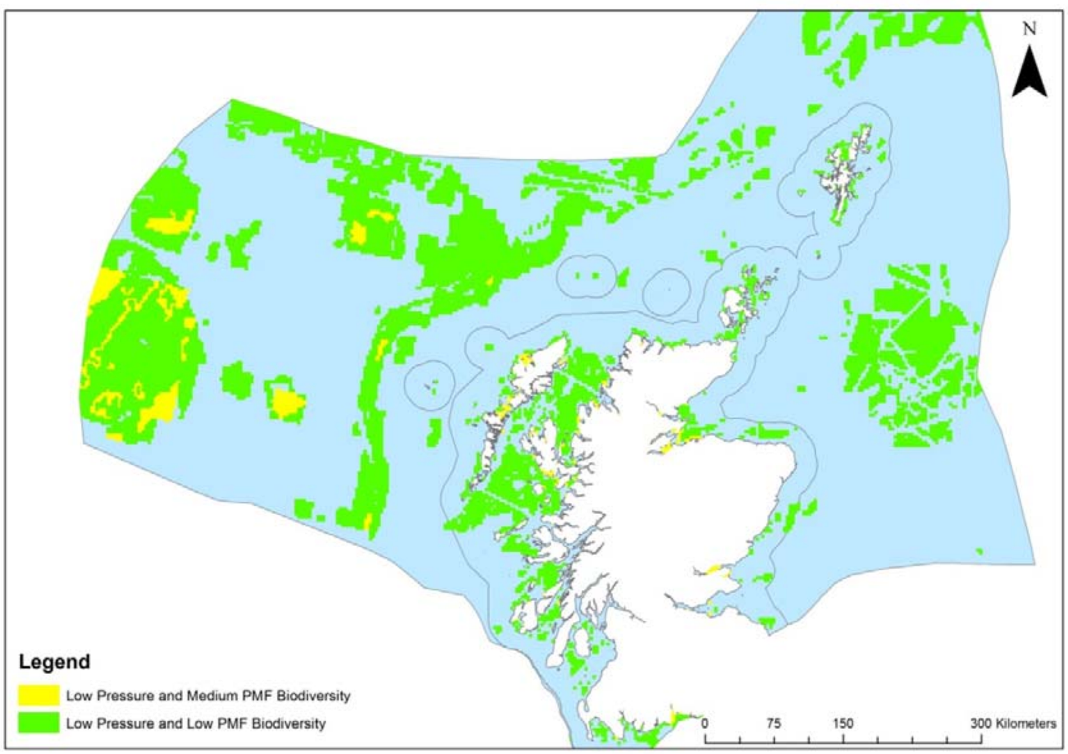


Figure 6.5: Areas of Low Pressure and Low/Medium PMF Biodiversity

Areas of Highest Pressure

Areas of highest pressure were mapped in relation to areas of potential PMF biodiversity. The results are shown in Figures 6.6 and 6.7. Figure 6.6 illustrates that there is only one specific area where very high pressures overlaps with areas of medium to high potential PMF biodiversity - Loch Ryan (Stranraer) on the south west coast of Scotland; representing a total of 15 km^2.

Figure 6.7 again shows that there is only one specific area of very high pressure overlapping with areas of low potential PMF biodiversity – a portion of the Montrose basin on the east coast, representing 3 km^2. Figure 6.7 also illustrates that there are three areas where areas of very high pressure overlap with areas of no potential PMFs, two located on the west coast and one on the east (Aberdeen); representing an area of 9 km^2.

Potential PMF Hotspots vs. Lowest Pressure

The areas of potential PMF hotspots, the areas of PMF hotspots and area of designated MPAs were overlaid in ArcMap. The areas of PMF hotspots and areas of designated MPAs were extracted from the potential PMF hotspot layer and discarded. The remaining layer represents the area of potential PMF hotspots that are currently not afforded any protection, are unknown, or have not previously been studied. These areas along with the MPA designations and reported PMFs are shown in Figure 6.8.

Area calculations indicate that there is a total area of 93,661 km^2 of potential PMF hotspots neither currently known/reported nor within a designated MPA; 34,244 km^2 of reported PMFs and 14,268 km^2 of designated MPAs (both of which are excluded from the potential PMF hotspot area calculation).

Reported PMF Habitat vs. High Pressure

Results show that there is 371 km^2 (calculated within the 3km x 3km grid) of PMFs already reported to OSPAR that are subject to high or very high human activity pressure as illustrated in Figure 6.9. The majority of potential highly impacted PMFs are located along the west coast of Scotland, with smaller areas impacted in Orkney, Shetland and on the east coast (primarily the Firth of Forth area).

Reported PMF Habitat vs. Low Pressure

Results show that there is currently 21,197 km^2 (calculated within the 3km x 3km grid) of PMFs already reported to OSPAR that are subject to low human activity pressure (Figure 6.10). Low impacted PMFs are located throughout the Scottish waters, with significant clusters off the west coast and in the North Sea.

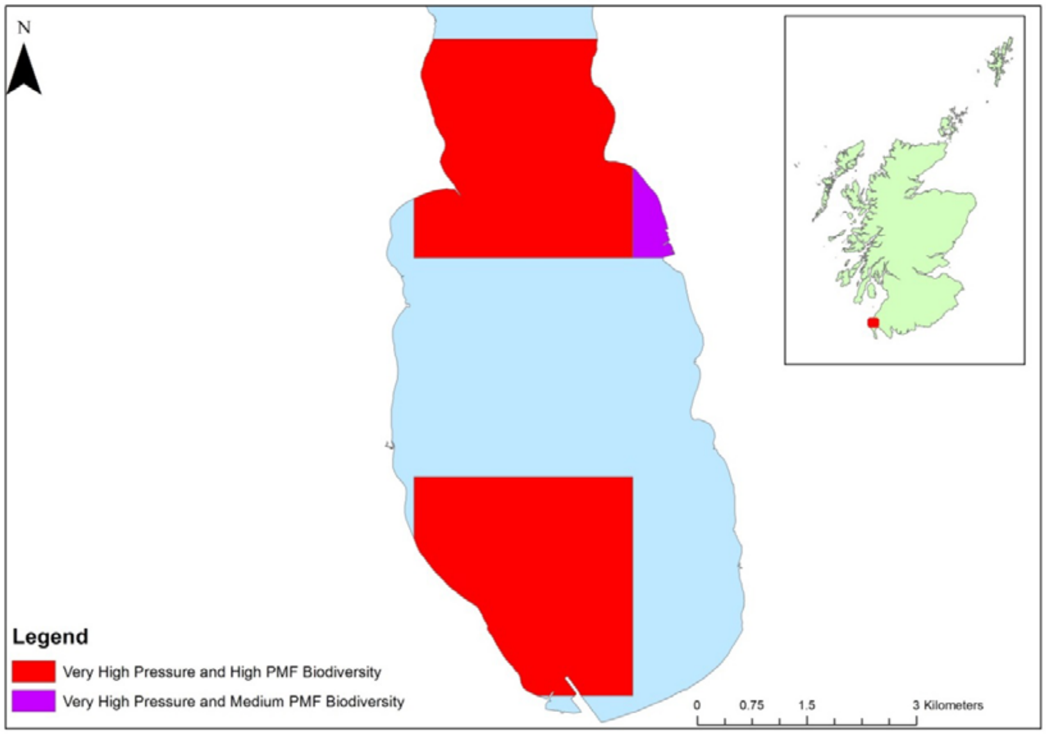


Figure 6.6: Areas of Very High Pressure and High/Medium PMF Biodiversity

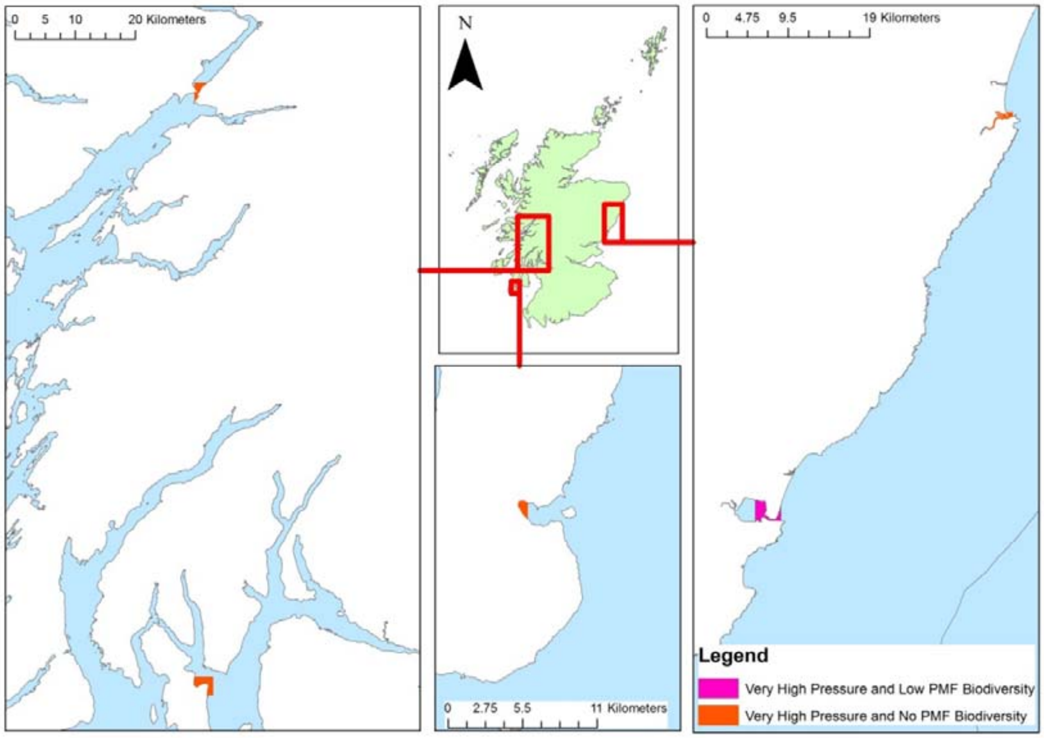


Figure 6.7: Areas of Very High Pressure and Low/No PMF Biodiversity

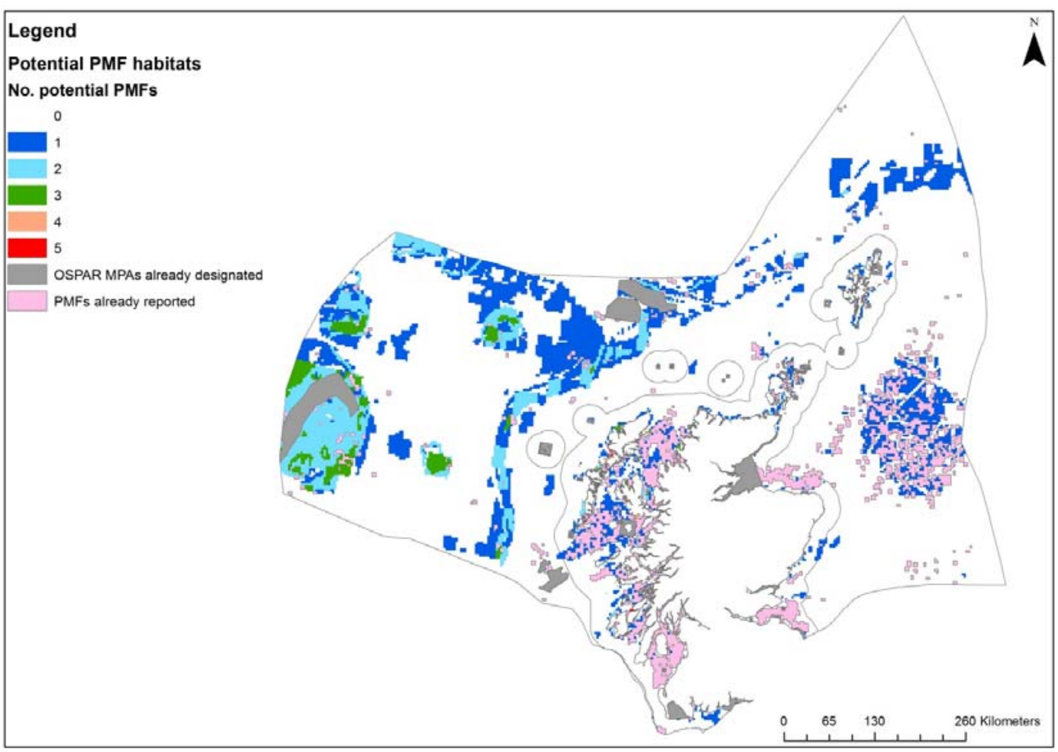


Figure 6.8: Modelled Co-occurring PMFs and Areas of MPAs and Known PMFs

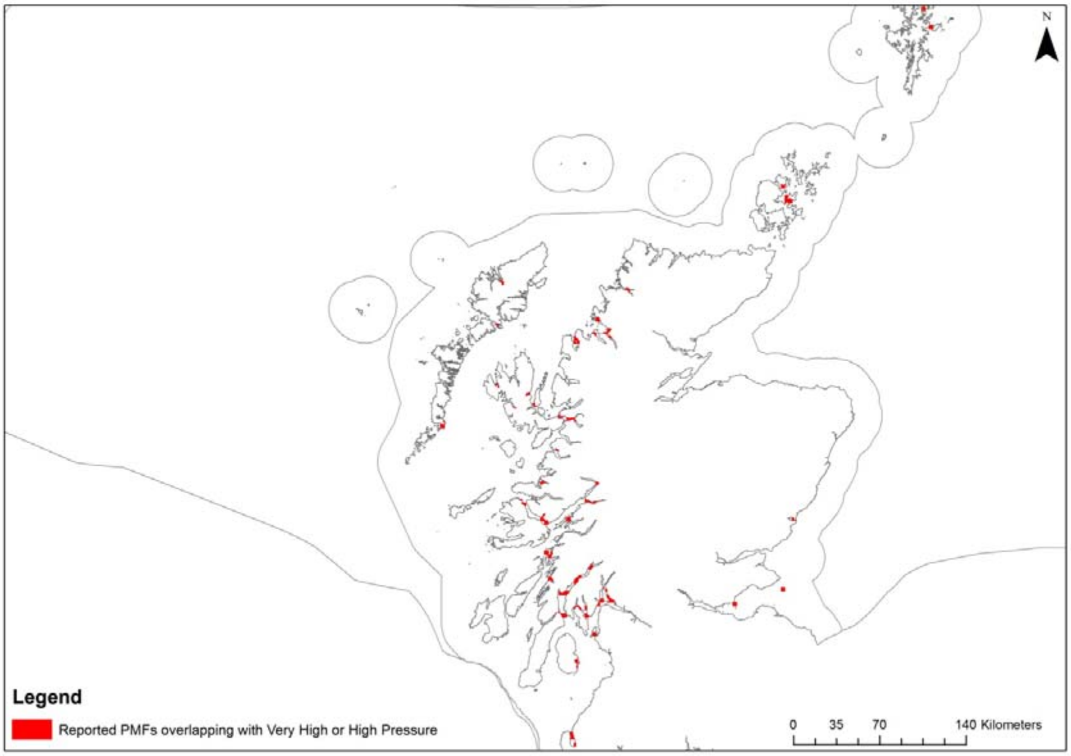


Figure 6.9: Reported PMFs overlapping with Areas of Very High Pressure

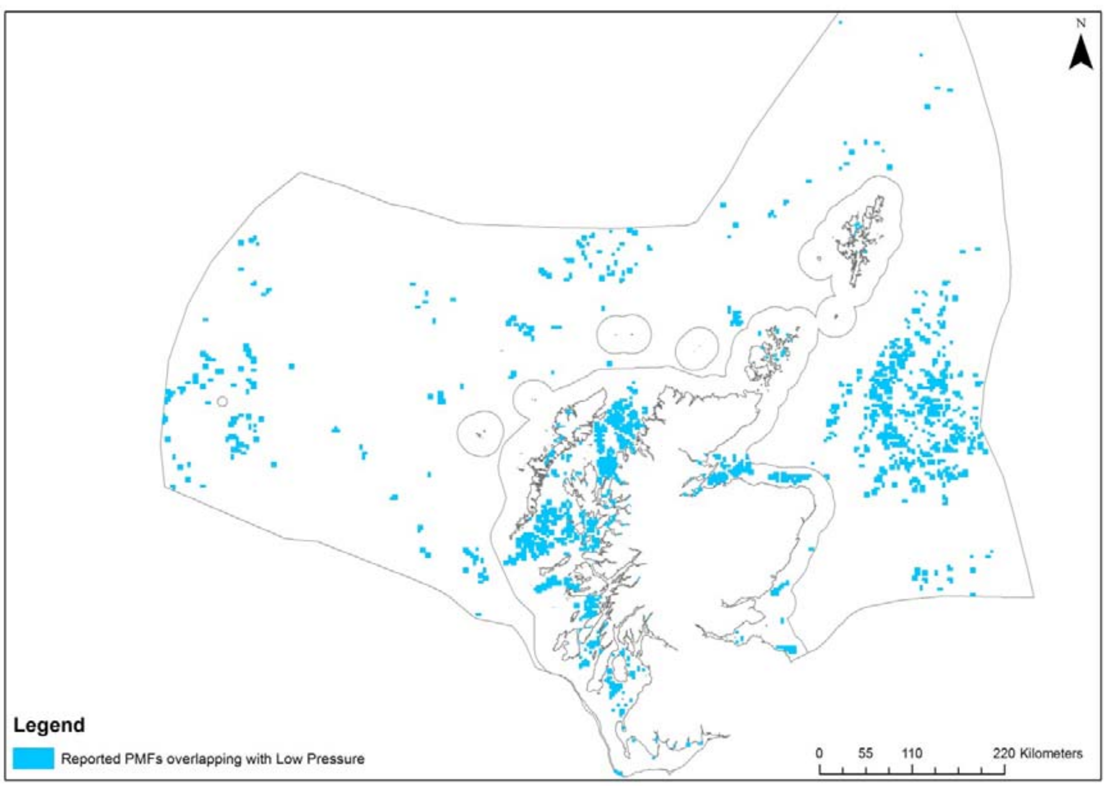


Figure 6.10: Reported PMFs overlapping with Areas of Low Pressure

6.3.3 Marine Region Assessment

The Marine Region Assessment (MRA) was carried out in order to ascertain which regions within the Scottish sea area are most important in relation to human activities and potential conservation protection. Scottish waters comprise 12 marine regions, as illustrated in Figure 6.11(a)

Figure 6.11(b) shows the area calculation for each of the 12 marine regions. Results indicate that Argyll and the South West marine regions are potentially the most important in terms of human activities (co-occurring) and that the Argyll, Clyde and West Highlands marine regions are potentially the most important in terms of marine conservation.

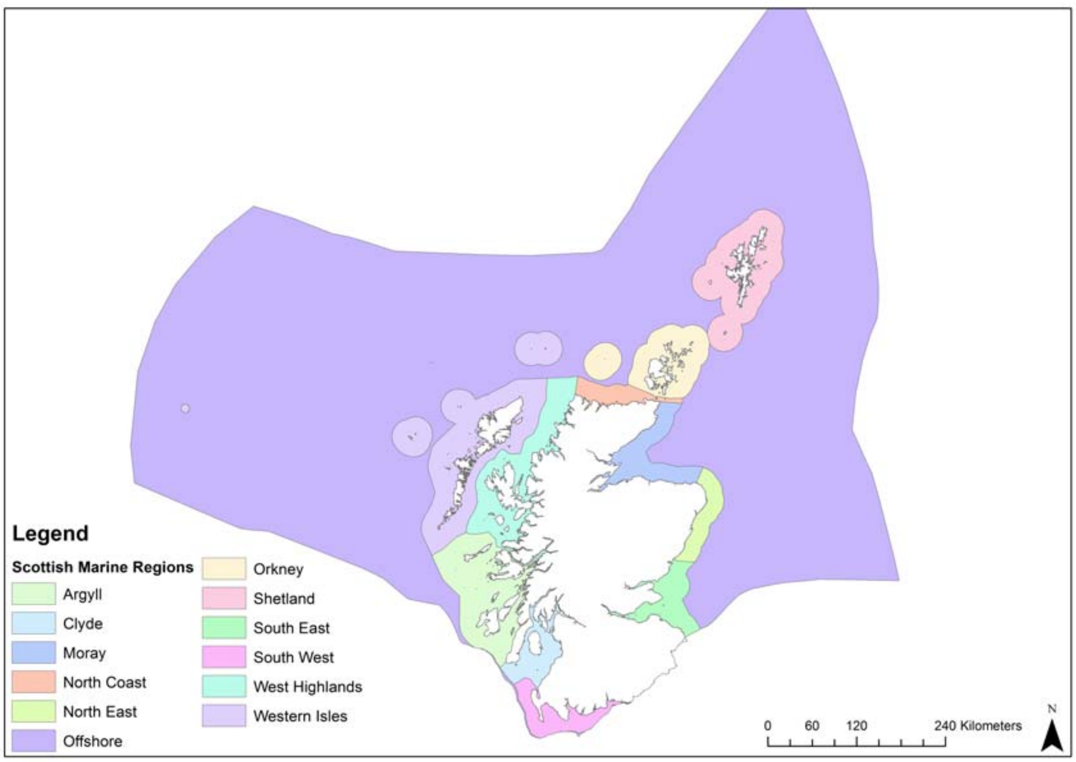


Figure 6.11(a): Scottish Marine Regions

Argyll		Conservation Hotspots (No. overlapping PMFs)					
Activities (no.)		0	1	2	3	4	5
0 to 1	Low	8698	1535	55	17	22	23
2 to 3	Medium	1255	214	33	82	14	65
4 to 5	High	3	2	0.2	0.0002	0.7	1
6 to 7	Very High	0.0001	0.1	0	0	0	0.02

Orkney		Conservation Hotspots					
Activities	Impact	0	1	2	3	4	5
0 to 1	Low	7367	380	35	0	0	0
2 to 3	Medium	1203	89	29	0	0	0
4 to 5	High	0.7	0.3	0.2	0	0	0
6 to 7	Very High	0	0	0	0	0	0

Clyde		Conservation Hotspots					
Activities		0	1	2	3	4	5
0 to 1	Low	957	1661	14	15	8	13
2 to 3	Medium	872	299	15	47	12	54
4 to 5	High	11	3	0.001	0.2	1	0.4
6 to 7	Very High	0.003	0	0	0	0	0

Shetland		Conservation Hotspots					
Activities	Impact	0	1	2	3	4	5
0 to 1	Low	10601	567	56	0	0	0
2 to 3	Medium	898	135	16	0	0	0
4 to 5	High	2	2	0.2	0	0	0
6 to 7	Very High	0	0	0	0	0	0

Moray		Conservation Hotspots					
Activities		0	1	2	3	4	5
0 to 1	Low	3660	874	56	87	87	0
2 to 3	Medium	890	183	4	3	20	0
4 to 5	High	0.4	0	0	0.01	0	0
6 to 7	Very High	0	0	0	0	0	0

South East		Conservation Hotspots					
Activities	Impact	0	1	2	3	4	5
0 to 1	Low	1874	570	112	120	0	0
2 to 3	Medium	1001	763	26	9	0	0
4 to 5	High	8	2	0.2	0	0	0
6 to 7	Very High	0.01	0	0	0	0	0

North Coast		Conservation Hotspots					
Activities	Impact	0	1	2	3	4	5
0 to 1	Low	2314	109	6	14	2	0
2 to 3	Medium	132	20	7	3	7	0
4 to 5	High	0.2	0	0	0	0.1	0
6 to 7	Very High	0	0	0	0	0	0

South West		Conservation Hotspots					
Activities	Impact	0	1	2	3	4	5
0 to 1	Low	1997	555	50	2	8	10
2 to 3	Medium	902	372	3	12	0.1	9
4 to 5	High	15	12	0.002	8	0	4
6 to 7	Very High	0.04	0	0	0.3	0	0.3

North East		Conservation Hotspots					
Activities	Impact	0	1	2	3	4	5
0 to 1	Low	2719	116	1	0	0	0
2 to 3	Medium	320	9	1	0	0	0
4 to 5	High	3	0.02	0	0	0	0
6 to 7	Very High	0.1	0	0	0	0	0

West Highlands		Conservation Hotspots					
Activities	Impact	0	1	2	3	4	5
0 to 1	Low	5003	4019	147	101	42	42
2 to 3	Medium	564	260	97	82	23	97
4 to 5	High	4	1	0.3	1	0.03	1
6 to 7	Very High	0.1	0	0	0	0	0

Offshore		Conservation Hotspots					
Activities	Impact	0	1	2	3	4	5
0 to 1	Low	293015	48920	20168	3328	0	0
2 to 3	Medium	16614	1397	14	0	0	0
4 to 5	High	66	4	0	0	0	0
6 to 7	Very High	0	0	0	0	0	0

Western Isles		Conservation Hotspots					
Activities	Impact	0	1	2	3	4	5
0 to 1	Low	17574	2538	243	109	15	11
2 to 3	Medium	247	125	66	29	13	8
4 to 5	High	1	0.001	1	0	0.01	0
6 to 7	Very High	0	0	0	0	0	0

Figure 6.11(b): Area (km^2) Co-occurring PMFs in Scottish Marine Regions

6.3.4 Prediction Indicators

The distribution maps are shown in Figures 6.12 and 6.13. The maps illustrate where areas of reported PMF (Figure 6.12) and potential PMF habitat (Figure 6.13) co-occur, representing PMF and potential PMF biodiversity hotspots respectively (PMF score and MS score).

The reported PMF distribution map (Figure 6.12) shows that there are areas where up to three PMFs may co-occur; with areas of highest PMF biodiversity primarily located along the west coast of Scotland. One area of high PMF biodiversity is located further offshore to the west of Scotland.

The modelled potential PMF map (Figure 6.13) illustrates that there are areas where there is the potential for up to 5 co-occurring PMFs to occur. The results also indicate areas of higher potential PMF biodiversity primarily occur on the west coast of Scotland, but with some additional areas appearing on the east coast.

The human activity results in Figure 6.14 show that there are up to 7 activities occurring simultaneously in some units of assessment. The majority of Very High management complexity (6 to 7 activities) occurred at limited locations along the west coast of Scotland. Low activity areas (0 to 1 activities) dominate the offshore region.

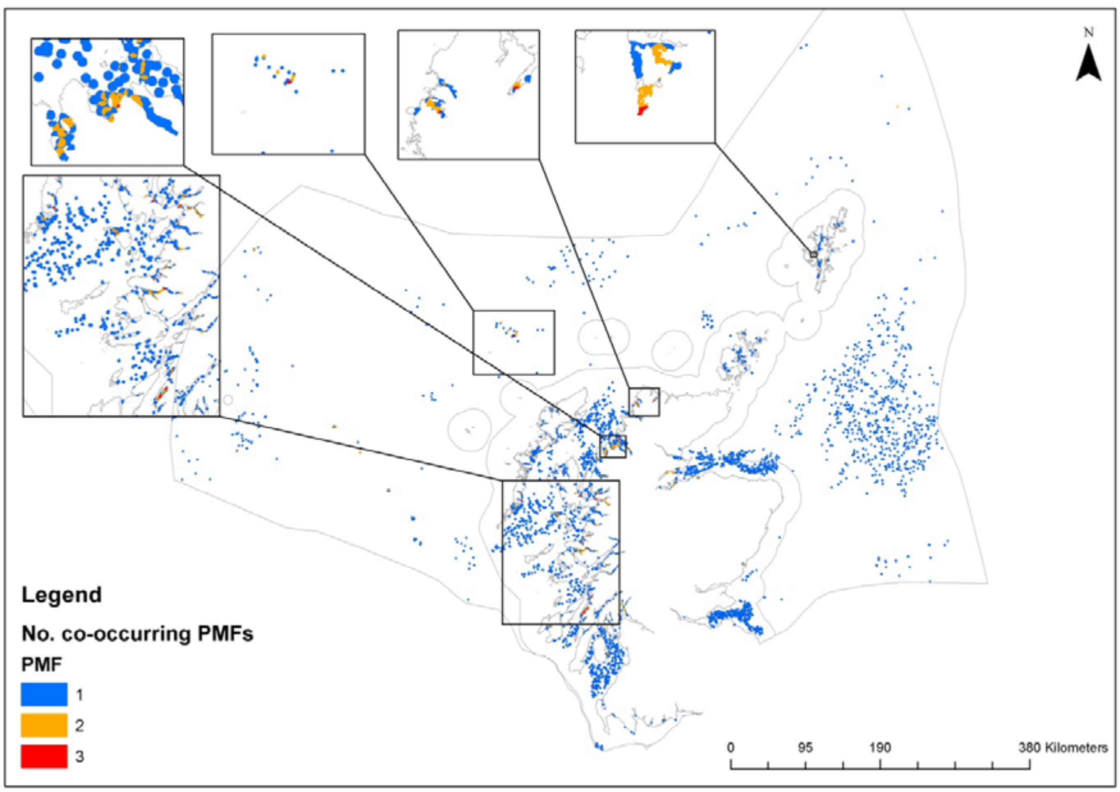


Figure 6.12: PMF Score – Number of Co-occurring PMFs

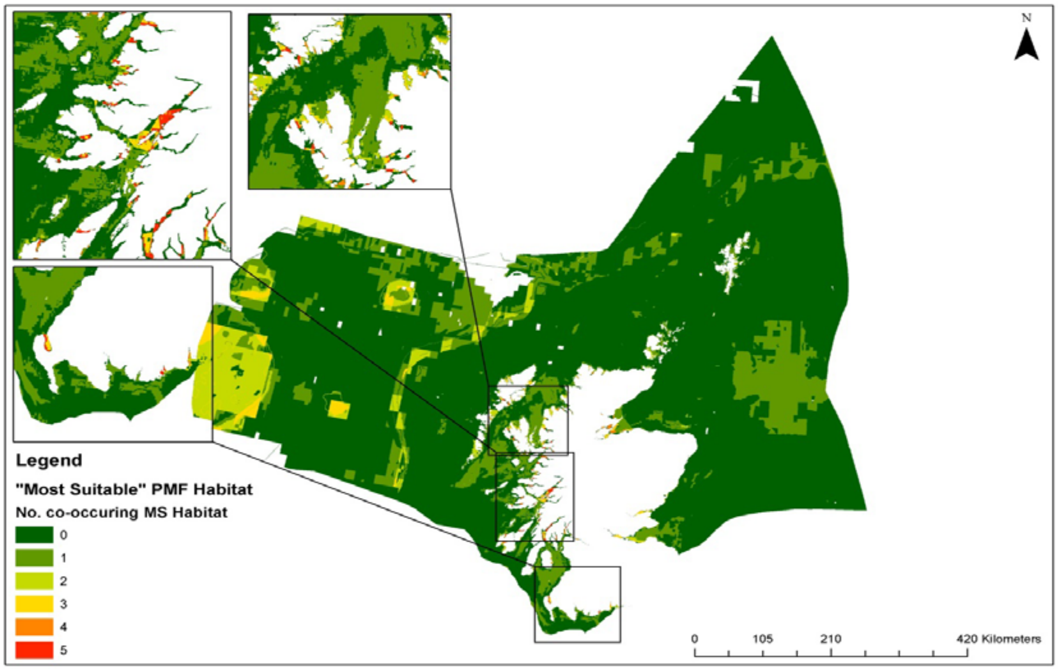


Figure 6.13: Most Suitable Habitat Score – Number Co-occurring PMFs

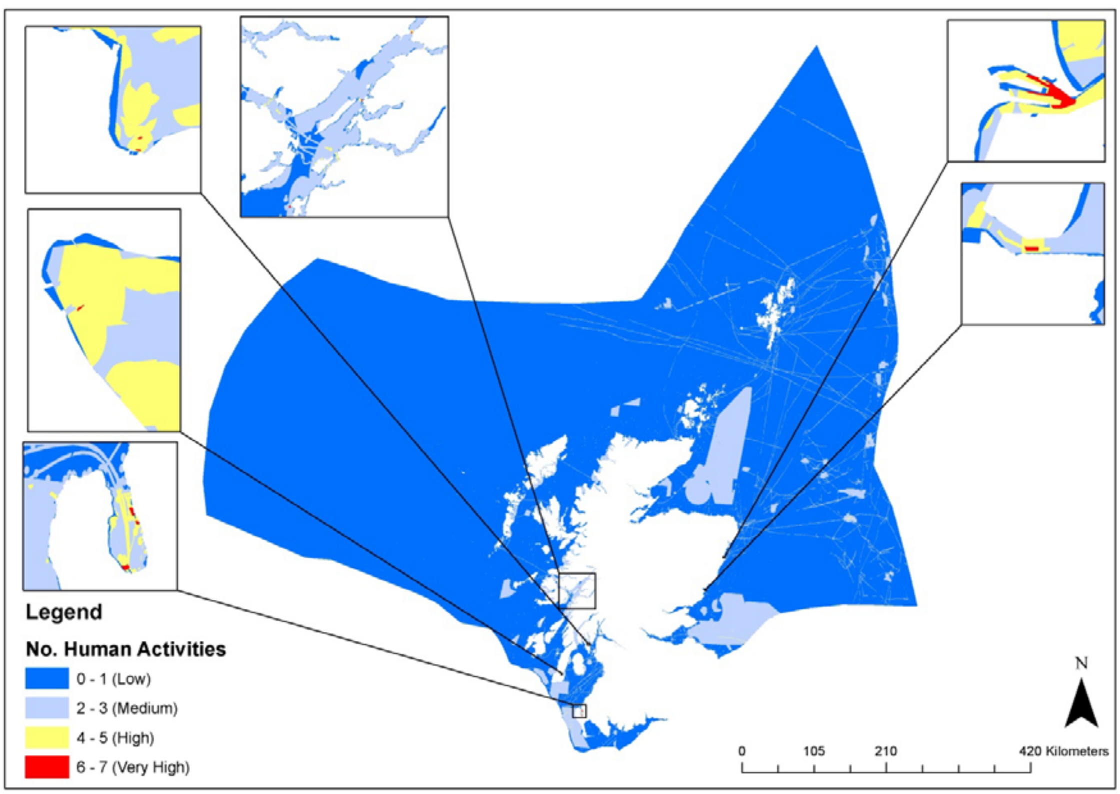


Figure 6.14: Human Activities Score – Number Co-occurring Human Activities

MPA Management Analysis

Table 6.5 shows the results of the spearman's rank correlation of the variables. Significant negative correlation ($p < 0.001$) was reported (casework events increased as the location score decreased) between the number of casework and the location of the MPA. This indicates that more management effort is required for MPAs in inshore areas compared with MPAs in offshore areas.

A positive correlation was reported between the number of casework events and the MS Score ($p <0.001$), the number of features ($p = 0.005$), and the PMF score ($p = 0.006$) (number of casework events increase as the MS and PMF score, and the number of features within an MPA increase). More management effort therefore appears to be required for MPAs with more conservation features. Furthermore, the modelled (MS) number of PMFs in an MPA was as good an indicator of management effort as the actual number reported. Therefore indicating that modelled data may be used in proxy for areas where actual survey data are lacking.

Table 6.5: Spearman's Rank Correlation between Variables

		No. of Casework	Location	Area of MPA	No. of Features	Type of Features	MC Score	PMF Score	MS Score 2009
No. of Casework	Correlation Coefficient		-0.426**	0.095	0.292**	0.025	0.082	0.291**	0.377**
	p		0.000	0.208	0.005	0.415	0.241	0.006	0.000
Location	Correlation Coefficient			0.101	-0.367**	0.087	-0.240*	0.026	-0.001
	p			0.194	0.001	0.228	0.019	0.413	0.496
Area of MPA	Correlation Coefficient				0.195*	-0.118	-0.244*	-0.145	-0.150
	p				0.047	0.156	0.018	0.108	0.099
No. of Features	Correlation Coefficient					-0.480**	-0.169	-0.130	-0.128
	p					0.000	0.073	0.134	0.136
Type of Features	Correlation Coefficient						0.239*	0.339**	0.235*
	p						0.020	0.001	0.021
MC Score	Correlation Coefficient							0.421**	0.095
	p							0.000	0.208
PMF Score	Correlation Coefficient								0.448**
	p								0.000
MS Score 2009	Correlation Coefficient								
	p								

*Correlation is significant at the 0.05 level

**Correlation is significant at the 0.01 level

The MC score and area of the MPA showed no significant correlation to the number of casework events (Table 6.5). This indicates that the number of licensed activities that occur within an MPA does not necessarily indicate that more management effort will be required to manage the MPA. This also indicates that larger MPAs do not necessarily require more management effort, supporting the results presented by (Ban *et al.*, 2011)

Results showed that there was significant negative correlation between the MC scores and number of casework events for the 10km and 5km buffered MPAs (Table 6.6). This indicates that the number of casework events decreased as the MC score increased in the general vicinity of MPAs.

Table 6.6: Spearman's Rank Correlation Coefficient for MC Score at 1, 5 and 10 km buffer around MPA

		10km MC Score	5km MC Score	1km MC Score	MC Score
No. of Casework	Correlation Coefficient	-0.355**	-0.330**	-0.210	0.082
	p	0.002	0.004	0.071	0.483

*Correlation is significant at the 0.05 level

**Correlation is significant at the 0.01 level

Overall, the results showed that the MPA location, MS Score and PMF score (in order of significance) were the best predictors of casework events. The number of features was also significant, but this data is not available on the iSNH SiteLink for the pMPAs at present and was therefore excluded.

The variable scores for the pMPAs were ranked in accordance with the predictor indicators with the results shown in Table 6.7.

Table 6.7: Proposed MPAs ranked by significant correlated variables (Prediction Indicator 1)

pMPA Name	Location	MS Score	PMF Score	Area	MC Score
Lochs Duich, Long and Alsh	1	2.010	0.854	43	1.39
Upper Loch Fyne and Loch Goil	1	1.538	0.307	94	1.88
Loch Creran	1	1.172	0.646	12	2.03
Loch Sunart	1	1.072	1.093	55	1.68
Loch Sunart to the Sound of Jura	1	0.821	0.174	800	1.63
North-west sea lochs and Summer Isles	1	0.773	0.446	615	1.33
South Arran	1	0.767	0.216	287	1.18
Wyre and Rousay Sounds	1	0.707	0.647	18	1.14
Mousa to Boddam	1	0.561	0.000	13	0.55
Papa Westray	1	0.410	0.007	35	1.19
Fetlar to Haroldswick	1	0.376	0.109	241	1.30
Small Isles	1	0.368	0.123	929	0.88
Eye Peninsula to Butt of Lewis	1	0.366	0.075	671	0.86
Skye to Mull	1	0.331	0.077	7276	1.10
Clyde Sea sill	1	0.229	0.070	718	1.58
Southern Trench	1	0.178	0.127	2296	1.19
Shiant East Bank	1	0.119	0.044	350	1.00
Loch Sween	1	0.073	1.039	41	0.98
Monach Isles	1	0.043	0.000	68	0.99

Table 6.7 (continued): Proposed MPAs ranked by significant correlated variables (Prediction Indicator 1)

pMPA Name	Location	MS Score	PMF Score	Area	MC Score
East Caithness Cliffs	1	0.037	0.000	117	0.80
Hatton-Rockall Basin	1	0.000	0.000	1304	0.00
Noss Head	1	0.000	0.000	9	0.25
North-west Orkney	1.5	0.019	0.006	4398	1.02
Western Fladen	2	1.000	0.124	724	0.64
South-west Sula Sgeir and Hebridean Slope	2	0.837	0.034	2114	0.13
Rosemary Bank Seamount	2	0.644	0.003	7508	0.00
Central Fladen (core)	2	0.597	0.041	216	1.04
SE Fladen	2	0.531	0.188	415	1.04
Geikie Slide and Hebridean Slope	2	0.522	0.001	2295	0.12
The Barra Fan and Hebrides Terrace Seamount	2	0.457	0.007	4766	1.00
Central Fladen	2	0.428	0.093	709	1.01
Faroe-Shetland Sponge Belt	2	0.104	0.003	6392	0.92
North-east Faroe-Shetland Channel	2	0.057	0.000	26968	0.96
Firth of Forth Banks Complex	2	0.010	0.002	2133	1.92
East of Gannet and Montrose Fields	2	0.000	0.002	1837	0.97
Norwegian boundary sediment plain	2	0.000	0.000	161	0.86
West Shetland Shelf	2	0.000	0.000	4064	0.93
Turbot Bank	2	0.000	0.000	234	1.00

Based on the linear regression predictor calculation, only the number of features, MC Score, PMF Score and MS Score (5km buffer) were concluded as showing normal distribution and a significant linear relationship. The calculation described in Section 6.2.4 was applied to the MC Score, PMF Score and MS Score (5km buffer). No data were available for the number of features at the pMPAs.

It was possible to calculate a range for the number of casework events that might be predicted for each of the pMPAs. These results were further condensed to produce a potential casework load value (Table 6.8). The results show that Lochs Duich, Long and Alsh, Loch Sunart, Loch Sween and Loch Creran may potentially require the most management effort, whereas the South-west Sula Sgeir and Hebridean Slope, Geikie Slide and Hebridean Slope and Rosemary Bank Seamount pMPAs, may require the least management effort. Of the top ten pMPAs in Table 6.8, six (highlighted) were directly attributable to the generated PMF score. The results were imported into

ArcMap 10.1 and mapped (Figure 6.15), illustrating the areas of highest average casework load.

Table 6.8: Proposed MPAs Calculated No. of Casework Events (Prediction Indicator 2)

Name	No. Casework (min)	No. Casework (max)	CW Load	average
Lochs Duich, Long and Alsh	78	86	<90	82
Loch Sunart	59	99	<100	79
Loch Sween	36	96	<100	66
Loch Creran	56	74	<80	65
Upper Loch Fyne and Loch Goil	55	70	<70	63
Wyre and Rousay Sounds	51	74	<80	63
North-west sea lochs and Summer Isles	46	63	<70	55
Loch Sunart to the Sound of Jura	46	53	<60	50
Mousa to Boddam	38	56	<60	47
East Caithness Cliffs	36	56	<60	46
Eye Peninsula to Butt of Lewis	42	47	<50	45
Noss Head	35	51	<60	43
Fetlar to Haroldswick	40	44	<50	42
South Arran	32	52	<60	42
Small Isles	32	45	<50	39
Firth of Forth Banks Complex	35	38	<40	37
Papa Westray	29	44	<50	37
Skye to Mull	31	42	<50	37
SE Fladen	18	49	<50	34
Monach Isles	28	38	<40	33
Shiant East Bank	26	40	<40	33
Southern Trench	21	45	<50	33
Western Fladen	7	57	<60	32
Central Fladen (core)	14	48	<50	31
Central Fladen	14	44	<50	29
The Barra Fan and Hebrides Terrace Seamount	13	45	<50	29
North-west Orkney	17	38	<40	28
Norwegian boundary sediment plain	3	48	<50	26
Turbot Bank	13	38	<40	26
East of Gannet and Montrose Fields	12	38	<40	25
Faroe-Shetland Sponge Belt	11	38	<40	25
North-east Faroe-Shetland Channel	10	38	<40	24
West Shetland Shelf	10	38	<40	24
Clyde Sea sill	2	42	<50	22
South-west Sula Sgeir and Hebridean Slope	-14	54	<60	20

Table 6.8 (continued): Proposed MPAs Calculated No. of Casework Events (Prediction Indicator 2)

Name	No. Casework (min)	No. Casework (max)	CW Load	average
Geikie Slide and Hebridean Slope	-12	47	<50	18
Rosemary Bank Seamount	-18	49	<50	16

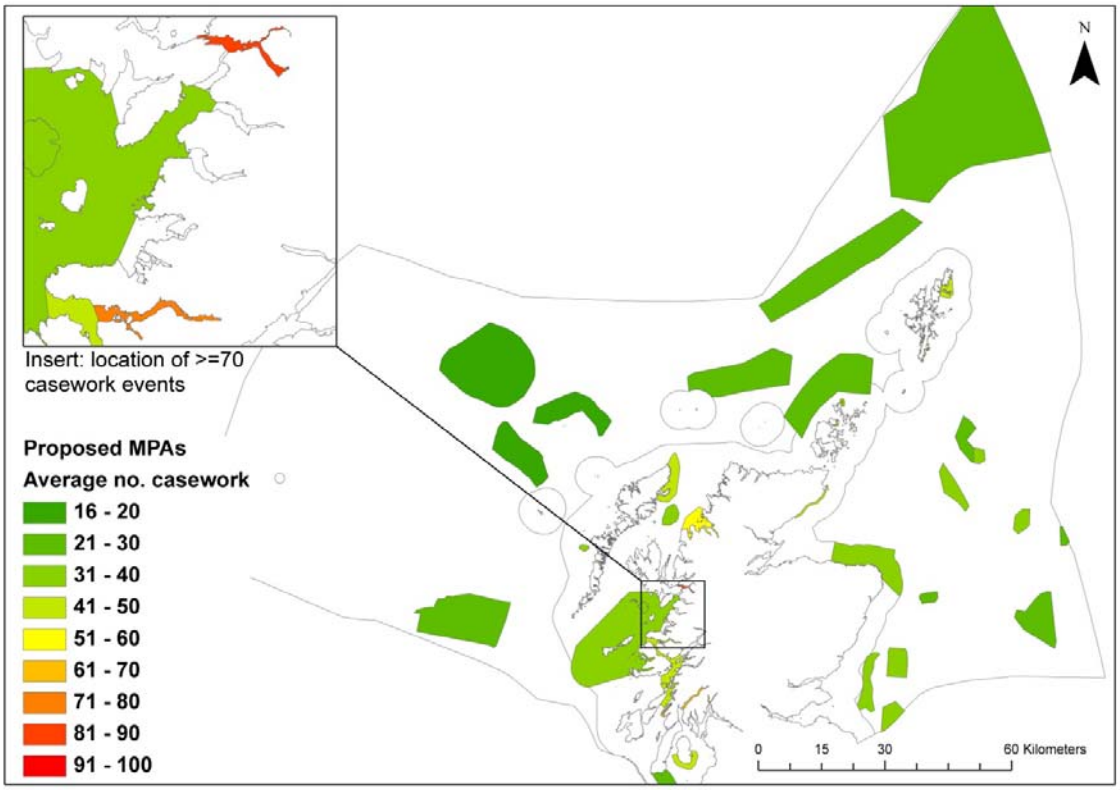


Figure 6.15: Average No. Casework Events at Proposed MPAs

6.4 Discussion

This first part of this study presented an overview of the distribution of human activities in Scottish waters in relation to potential and known conservation hotspots. The seas around Scotland support a variety of flora and fauna, some of which are of conservation importance; and they are also extremely important from a commercial perspective, with many activities occurring simultaneously (McWhinnie *et al.*, 2013). It is widely accepted that human activities place heavy pressure on global marine ecosystems

(Korpinen *et al.*, 2012) and subsequently, an increase in human activity equals increased pressure on the marine environment.

Details of cumulative impacts of activities on the marine environment in Scottish waters are limited, however this study has shown how relatively simple methods can be applied to currently available data to make initial assumptions of potential impacts to habitats, in relation to PMFs (or PMHs), to better guide conservation managers and policy makers.

The second part of this study is the first to attempt to evaluate the cost-benefit of a proposed MPA network based on the subsequent effort required to manage it. Scottish Seas are thought to be amongst the most habitat and species rich in the North East Atlantic countries (Hiscock, 1996) and are correspondingly of disproportionate economic importance to its population (Scottish Government, 2011).

The present study therefore provides a rational framework for (typically resourced constrained) governments and their agencies to evaluate the consequences of selecting particular MPAs for designation, beyond the biodiversity and socio-economic considerations previously suggested, e.g. (Richardson *et al.*, 2006)

6.4.1 Priority Marine Features and Human Activities

The selection of MPAs for conservation of biodiversity is generally made on the basis of protecting species and/or habitats of perceived conservation importance or vulnerability; therefore requiring extensive information on the spatial location and range extent of each habitat (Ross and Howell, 2012) and also knowledge of their potential "status" (e.g. are the habitats likely to be impacted by human activities?).

Although the UK is generally considered to be good at implementing marine conservation strategies; and undertakes significant research in the marine environment; understandably, areas of marine environment still remain poorly studied due to cost, access or time implications. Therefore, predictive habitat modelling can be applied in an attempt to fill these survey gaps.

The Maxent model outputs in this study provide an overview of "Most Suitable" habitat for eight PMFs in Scottish waters; and overall, the trained model can be interpreted as showing a good predictive range. Although there are limitations with using SDM methods, particularly regarding input data quality (as discussed in Chapter 4), generally the method applied here is considered to provide a robust and defensible means of 'filling in gaps' (Ross and Howell, 2012).

This study was not concerned with the potential distribution of each PMF individually, but rather with the potential areas that may benefit most from potential conservation management; or those areas that will be most easily managed or designated.

It is assumed that areas with the least human activities will hopefully provide the best representation of a "pristine" environment. From the results, it is evident that areas around the coast are highly used and contain the greatest quantities of human pressures, whereas the areas offshore are least used. In addition, areas along the coast contain the most PMFs, and areas offshore contain the least. This is most likely attributable to the amount of survey work that has been carried out within coastal waters compared to the deeper offshore waters through ease of access, or in relation to industry targeted (or funded) study.

6.4.2 Pressure-Ecosystem Analysis

The assessment of human activities vs. the area of potential PMF hotspots provides an overview of areas that may be most suitable for future marine conservation management. The areas of high potential PMF biodiversity in relation to low human activities may hopefully represent areas of future search with regard to suitable MPAs. It is assumed that these areas may best represent habitat in close to "pristine" condition as they are expected to be least impacted by human activities.

Another aspect of this study was to determine where within the modelled potential PMF dataset, PMFs are already known and where MPAs have already been designated; ultimately providing an overview of potential target areas for additional research, potential conservation designations or simply tighter management strategies. It is anticipated that this study may provide an illustration of potential PMF "corridors", therefore providing the best estimation of a coherent MPA network.

There is currently 34,244 km^2 of PMFs (within the 3km x 3km grid) reported, of which 2,961 km^2 (12%) fall within a designated MPA (whether to PMF specific designation or not). The model output calculated a total of 126,306 km^2 of potential PMF habitat. Based on these outputs it was possible to determine that current MPAs do capture areas of "Most Suitable" PMF habitat; in fact, 9,730 km^2 (8%) of potential PMF habitat currently fall within an MPA designation, and 20% (25,527 km^2) is overlapped by reported PMFs.

Of the PMFs that are illustrated as being minimally impacted by human activities, 8% fall within a designated MPA, indicating the significant potential for more extensive marine conservation protection of habitats that may represent Good Environmental Status (GES) under the MSFD.

In addition, the PMFs that are potentially impacted by human activities (high or very high), 11% falls within a designated MPA, indicating that these MPAs are not exclusion zones for marine conservation protection purposes (particular to benthic habitats), or the activities occurring in these areas are not directly or physically impacting on the benthic marine environment (e.g. shipping).

6.4.3 Marine Region Assessment

With the principles of marine spatial planning in mind, the area of potential priority marine habitat within each of the 12 Scottish Marine Regions was calculated to determine which regions are most important in terms of commercial activity and marine conservation. This assessment may enable a more focussed approach to marine conservation management within the regional and national marine plans.

From a national context, the Scottish Marine Plan states that (Scottish Government, 2011):

"Development should aim to avoid harm to marine ecology, biodiversity and geological conservation interests, including through location, mitigation and consideration of reasonable alternatives" with particular weighting to protected sites and priority species/habitats applied.

From a qualitative point of view, the MRA undertaken within this study has shown that each marine region will potentially require different strategies when considering cumulative impacts and MPA designation and management (with particular emphasis on benthic habitat and species); a concept that is not acknowledged within the emerging national marine plan. However, it is a concept that could be fully integrated into the regional marine plans.

Presently, regional marine plans have yet to be implemented, with the exception of the Shetland Marine Spatial Plan (NAFC Marine Centre, 2012). This plan outlines details of what measures will be taken into account to allow for sustainable development (planning applications etc.) within areas of conservation interest (both within and outwith designated sites) – but does not seem to specifically consider benthic habitats/species – instead, there appears to be a broad brush of measures applied, stating (NAFC Marine Centre, 2012):

- Developments or activities that would have a significant adverse direct or indirect effect on any important species of animal (or their actively used breeding, feeding and roosting habitats) or plant or habitat out with designated nature conservation areas will only be permitted:
  - if it can be subject to conditions that will prevent damaging impacts on wildlife habitats or important physical features; or,
  - the creation of a replacement habitat of equal habitat value could be imposed as a planning obligation to mitigate the effects of the proposed development; or,
  - where there is no reasonable alternative or less ecologically damaging location and the reasons for the development clearly outweigh the value of the habitat/species by virtue of social or economic benefits of regional importance.

It therefore needs to be acknowledged that each marine region's PMF hotspots or individuals will require different management measures as it will depend on what activities occur within which regions. Applying the same management across the board may result in more management effort being needed if meaningful mitigation measures are not implemented correctly and in full.

6.4.4 Predictor Indicators

MPA Management Analysis

From the results, the null hypothesis that "the level of management complexity within an MPA does not have a significant relationship to the MPA's management effort" was retained. This suggests that an MPA will not be any more time-consuming to manage if more licensed activities occur within it. This counter-intuitive outcome suggests that, in general, the stakeholder engagement and/or licence conditions used to set up the extant MPAs were, in general, compatible with the conservation objectives of the MPAs, or that they are not known to conflict, and hence have not required further recorded management activity (casework). However, Compatibility of conservation objectives with activities can often only be fully evaluated with feedback from an appropriate monitoring programme. Although some management activity (e.g. sector-wide fisheries consultations etc.) may be captured within other casework or stakeholder engagement which did not get logged at the scale of the MPA, their absence in the present analysis is unlikely to have affected the general findings.

In the marine environment no 'physical' boundaries exist in reality and exclusive private ownership of space is less common, therefore the relationship between the number of casework events and the management complexity within 5 and 10km of the MPA provided a significant relationship with management effort that might not be expected in terrestrial protected areas. One explanation may be that areas with high numbers of anthropogenic activities may ultimately attract more activity (e.g. through the development of coastal amenities and infrastructure enabling more use by different activities, such a ports), which therefore needs to be reconciled against the conservation objectives of the adjacent MPAs (i.e. casework events). Overall, the activities adjacent to the MPA influence the effort required to manage the MPA.

The South Arran pMPA was ranked 13th (out of the 37 pMPAs; Table 6.7). As an MPA proposed by the local community, South Arran may have been expected to require relatively little subsequent management effort. The South Arran pMPA, however, is a multifunctional site which has been proposed for designation by a community of people who are not the sole users of the area and as such the proposal has proved controversial with wider interests, such as the Clyde *Nephrops* fishery (JMP, 2008). The casework load (management effort) therefore may well be as predicted here for South Arran. However, it is important to recognise that the relationship between contention in the consultation and pre-designation process of an MPA and the subsequent post-designation management effort of that MPA has not been evaluated here. It is entirely possible that more politically contentious MPAs may attract a greater amount of casework than predicted. This scenario may be addressed in future through assessment of weighted variables, particularly the MC score. It is also worth considering that some particularly contentious MPAs may get dealt with by other organisations (for example, Marine Scotland or the Joint Nature Conservation Committee; JNCC) and hence the full casework activity associated with them may not have been recognised based solely on the SNH system this study has used. A number of sites, may also have been involved in issues that affect multiple sites, therefore it is likely that the casework may only have been logged against one MPA, rather than all involved.

In addition to the management complexity null hypothesis, this study also set out to test whether location of the MPA, and the number and type of features within an MPA would influence MPA management effort. This study rejects the null hypotheses that management effort would not increase a) as the number of qualifying features within the MPA increased; b) with increased proximity to the coastline (e.g. offshore vs. inshore); and c) if more publically appealing features occur within the MPA.

It is possible that the number of features in an MPA increases the management effort as more monitoring may be required to account for the individual features within the different casework events (e.g. planning applications), which may inevitably require more overall management. In addition, this will also relate to the type of features in the MPA, given that different types of features will require different management methods to be applied and links to the public perception of them.

The rejection of the null hypotheses regarding location of and type of features within an MPA is potentially influenced by the public as well as the stakeholders. It is likely that public perception and involvement play a big role with regard to these factors on MPA management effort. The public generally find marine mammals and birds more endearing, for example, as they are more aesthetically appealing, easier to see, and more prevalent in people's minds when considering the seas (Bianchi and Morri, 2000). This in turn is likely to result in greater pressure for management effort, whereas benthic habitats, which are harder for the public to perceive, or considered rare or threatened, are likely to attract less pressure for management effort. In addition, the public are likely to be more interested in MPAs that are on their 'doorstep' (i.e. inshore) rather than those which are miles offshore.

In the present work, the number of features, the MPA location and the type of features were excluded from the prediction calculation as i) data on the number of casework events was incomplete (number and type of features), ii) they did not show a significant linear relationship with the number of casework events (type of features) or iii) the data did not show normal distribution (location). This study suggests that these variables would be worthy of further investigation.

6.5 Conclusions

These studies have i) shown that there are a number of areas that may be suitable for further investigation with regard to the establishment of MPAs and general marine management; ii) identified areas of potential PMF hotspots that are likely to be least impacted by human activity; and iii) developed a predictive calculation method that may be applied to proposed or future MPAs to provide an assessment of the level of management that might be required. These assessments are not definitive but it does provide an overview that may assist in the decision of MPA management options and the assignment of management resource.

It can be concluded that Scotland has carried out a significant amount of work with regards to the designation of MPAs and the identification of PMFs. This study has provided evidence to support that there are areas suitable for designation to further complement the already established MPA network, and potentially provide the best route towards achieving GES within the set timescale, and therefore preventing wasted effort.

It may be the fact that areas that are least influenced by human activities may not require MPA protection, as human activities may not be possible within these areas now or in the future – therefore management effort may be wasted. In the same vein, areas that are already potentially impacted by human activities, management may be irrelevant, as the habitat may not represent GES nor be suitable for restoration if already damaged.

Areas that are identified as being of high conservation importance (whether high PMF biodiversity, or extent of a single PMF) would benefit from further research with regard to potential future human activities. For example, areas off the continental shelf that may potentially be exploited by fisheries or energy extraction in the future; therefore providing a strategy to maintain GES whilst providing a sustainable economic-ecosystem balance.

With logged experience of the present system of management effort assessment, it is possible to evaluate options within an MPA network to achieve the most cost effective option that meets the biodiversity and socio-economic objectives of the MPA network: some MPAs are likely to be more efficient than others in terms of management time. This has not been the explicit intent of the Scottish MPA network proposals evaluated here, so it is not possible to consider the relative costs of the different options. However, within the present study it is possible to see that some MPAs are likely to be more efficient than others in terms of management time. Richardson *et al.* (2006) considered how options for networks can be evaluated to minimise the socio-economic impacts of protection. Here we considered a potential method for assessing the management efficiency of different network options.

A forecast of management effort provides a useful indication of the relative cost of the ensuing monitoring and management resources required within an MPA network. The more activities there are that are a potential concern to the achievement of the conservation objectives (and likely to generate casework events) the more monitoring feedback is likely required to provide confidence that the objectives are being met. An intuitively attractive concept also emerges from the present work: MPAs in busier places are no more likely to require increased effort to manage when compared to those in quieter areas, irrespective of existing licensed activities occurring within them.

6.6 Chapter 6 Summary

- Firstly, understanding where human activities occur simultaneously within the MPA network may allow for the development of a suitable cumulative assessment methodology and selection of a suitable management strategy.
- Areas of high activity and high conservation importance may not be the easiest to manage
- However, statistical analysis of existing data can be applied to provide a judgement of potential future management effort of MPAs and PMFs
- Results showed that MPAs with high levels of human activity may not actually be as time-consuming to manage as originally thought
- Developing a method for understanding interactions between human activities and the marine environment may lead to the requirement for management prioritisation that will enable policy makers to better apply limited resources to achieve set conservation objectives and an effective planning system

Chapter 7. Understanding Genetic Connectivity and Diversity

7.1 Introduction

Management of species of conservation or commercial importance may require detailed knowledge about their genetic structure and status, as this information may be of use in informing the successful maintenance of these populations through breeding programmes (Jiale *et al.*, 2009) and /or restoration of habitats (Roberts *et al.*, 2011). In addition, understanding population connectivity has become a major factor in determining and defining threats to marine biodiversity and is crucial to the marine conservation and management process (Schunter *et al.*, 2011; Weersing and Toonen, 2009).

One way in which genetics should complement ecological approaches to conservation, is through the use of molecular techniques to supplement demographic and population studies (Salgueiro *et al.*, 2003) and an effective strategy for the conservation of a particular species should, in part, be determined by information gathered on its genetic structure, especially the spatial distribution of variability (Salgueiro *et al.*, 2003).

Connectivity can be defined as the genetic exchange of individuals and their propagules by means of migration and dispersal (Schunter *et al.*, 2011). In the marine environment this is principally driven by pelagic larval stages and is therefore directly influenced by oceanographic processes such as currents, winds or eddies (Palumbi, 2003). However, patterns of dispersal of pelagic larvae remain poorly understood due to the difficulty of obtaining direct measurements of movement and behaviour of these tiny propagules. This is especially problematic in the marine environment where sessile or sedentary species (such as *M. modiolus*) have a bipartite life cycle, producing tiny planktonic propagules that are virtually impossible to track using currently available technologies (Weersing and Toonen, 2009) or over large distances (Bell, 2008).

In principle, species with widely dispersing larvae should be genetically homogenous over large spatial scales, and therefore potentially reducing their ability to adapt to local conditions. However, if pelagic larvae are not widely dispersed and are instead retained near their natal population either by behavioural or by physical oceanographic processes, then populations would essentially have a greater chance for genetic differentiation and local adaption. If this local retention persists over many generations then new species may be formed, or at least lead to the requirement for different management and/or conservation strategies (Taylor and Hellberg, 2003).

7.1.1 Marine Spatial Planning and Connectivity

The overarching objective of Marine Spatial Planning (MSP) is to provide a tool which will enable resolution of conflicts between the industry sectors and individuals competing for their claim to use certain areas of the seas around Scotland (and the UK). Ultimately, the UK Governments will need to be able to identify those industries/sectors which will get priority in certain areas. This would include, for example, priority fishing zones; priority renewable energy zones; priority nature conservation zones (Marine Conservation Zones, MCZs and MPAs).

There is a requirement to establish an ecologically coherent network of protected areas (MPAs and Natura 2000 sites) under the UK Marine and Coastal Access Act 2009, the OSPAR convention and the MSFD. Maintaining this coherence will not only require the management of connectivity corridors in relation to mobile species, but should also consider the genetic connectivity of non-mobile species (e.g. biogenic reefs, of PMHs etc.). Failure to maintain connectivity, as a result of MSP or climate change, of all protected areas, will ultimately lead to failure of the required network.

McLeod *et al.* (2009) suggested that biological patterns of connectivity should be taken into account when designing MPA networks and with regard to the impacts of climate change to facilitate mutual replenishment and recovery from disturbance. In addition, they suggested that future connectivity patterns should be modelled so that measures can be taken to protect areas and facilitate expansion and migration (McLeod *et al.,* 2009), as discussed in Chapters 4 and 5 of this thesis.

Although MSP does not obviously involve the placement of physical barriers or boundaries into the marine environment, the boundaries of the planned ‘zones’ will be managed (whether voluntarily or governmentally) and will still represent a potential barrier to the movement of species between sites. This connectivity of sites enables replenishment and maintenance of genetic diversity of these sites. Removal of these important pathways may lead to a number of problems including loss of a species in one area due to disease or lack of recruitment. For example an MPA created around an Island, may allow for more effective management compared to the open ocean, due to the fact that the boundaries can be more clearly defined; however, they may make populations more susceptible to environmental change, extinction (in the worst case) (Schunter *et al.*, 2011) and potential inbreeding if population sizes are small; because influx of larvae and adults (in the case of mobile species) is likely to be reduced (Bell, 2008). In addition, placement of industry zones that potentially alter oceanographic processes (such as marine renewable technologies) may ultimately influence the trajectory of propagules. This may lead to the larvae settling in new areas, and therefore reducing influx of larvae and replenishment of established areas. Importantly, the establishment of small and scattered MPAs that do not consider population connectivity may have a limited effect on the protection of the marine environment (Schunter *et al.*, 2011). Figure 7.1 illustrates how the placement of ‘zones’ may hinder the connectivity of the sites.

It is acknowledged that there is a need to understand how the location, geographical extent and connectivity of key habitats and species may impact on their conservation needs and therefore on the choice of Ecosystem Based Management (EBM) tools best suited to protect and enhance them (Harrald and Davies, 2010).

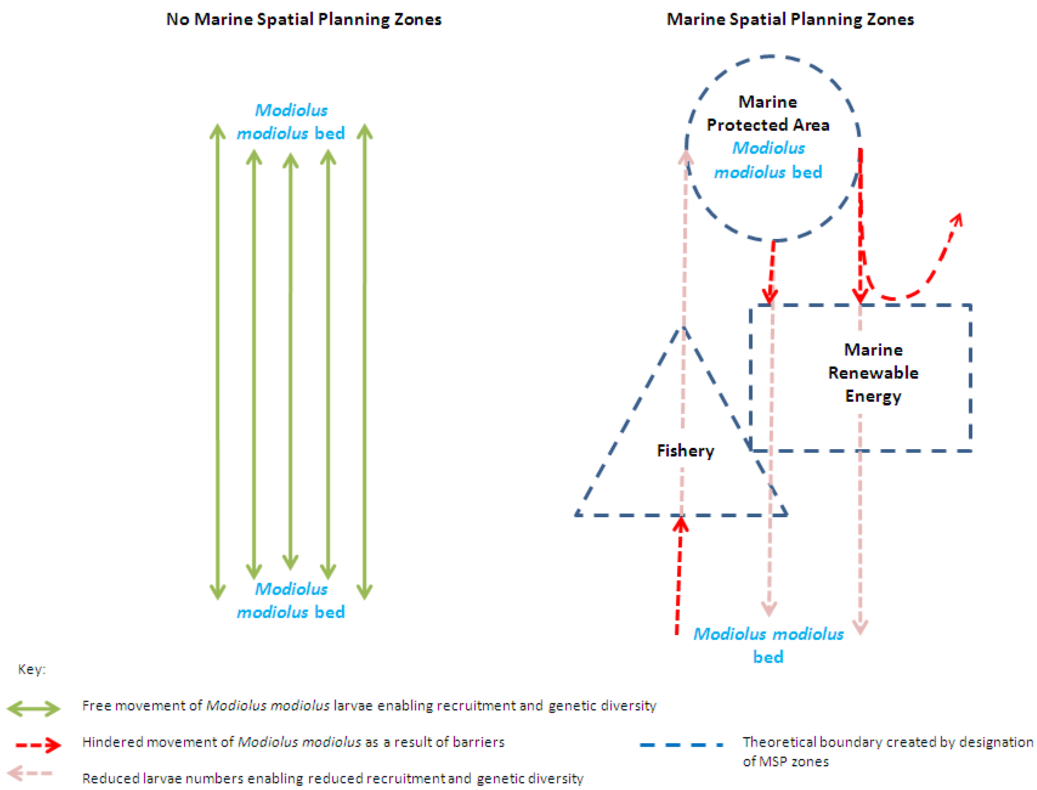


Figure 7.1: Schematic illustrating possible hindrance to species movement and distribution as a result of Marine Spatial Planning.

7.1.2 Aims and Objectives

- **Research Overview**: Understanding connectivity is essential in order to select the most appropriate management measures for a priority habitat. Decision makers can use the results to determine if *Modiolus* beds can be managed separately or jointly; and whether restoration programmes can be implemented.

 Key tasks:

  - *Investigate whether populations of the feature are connected*

The aim of this study is to understand whether existing *M. modiolus* reefs/beds at varying locations around the UK are linked genetically; which beds are isolated in terms of an influx of genetic material; and which beds are essentially connected. This will be achieved by the development of microsatellite markers. These results will give decision makers the knowledge required to facilitate sustainable MSP zones and a successfully connected MPA network, without interfering with or influencing the natural migration/movement pathways of *M. modiolus* larvae.

A M.Sc. Thesis prepared by Jones (2011) carried out preliminary identification of microsatellite regions for marker development for *M. modiolus*. During this particular study Jones (2011) carried out the initial stages of microsatellite marker development through the sequencing of a number of *M. modiolus* DNA samples, the identification of microsatellites within the DNA and the design of 5 primers for these microsatellites.

It was intended to use this initial work to develop primers and to use Polymerase Chain Reactions (PCR) to test the primers on the DNA samples collected from the sites outlined in Section 7.4.

Additionally, it was decided to carry out a small complementary investigation into the mitochondrial gene (CO1) to determine whether differing clades within the Atlantic population could be identified, therefore building on work carried out by Halanych *et al.* (2013), see section 7.2.

7.1.3 Microsatellites and Ecology

Introduction

Microsatellites, also known as simple sequence repeats (SSRs) or short tandem repeats are repeating sequences of 2-6 base pairs of DNA and are used as molecular markers in genetics for population studies (Selkoe and Toonen, 2006).

An example of a microsatellite marker (short tandem repeat) is shown in bold below:

DNA sequence

tgccgatggtacctgc**agtagtagtagtagtagtagtagtagt**aatcgccgatgacctggttgac...

acggctaccatggacg**tcatcatcatcatcatcatcatcatca**ttagcggctactggaccaactg...

Flanking Region

Microsatellite markers have been identified as an important tool for the evaluation of levels and patterns of genetic diversity in a number of aquatic species such as the Chinese freshwater pearl mussel *Hyriopsis cumingii* (Jiale *et al.*, 2009), the harmful dinoflagellate *Alexandrium mimutum* (Casabianca *et al.*, 2012), the Pacific oyster *Crassostrea gigas* (Li *et al.*, 2006; Yu and Li, 2007), the marine mussel *Mytilus galloprovincialis* (Lado-Insua *et al.*, 2011; Diz and Presa, 2009; Cruz *et al.*, 2005); the gastropod *Nucella lapillus* (Bell, 2008); the acorn barnacle *Semibalanus balanoides*

(Bell, 2008; Bell and Okamura, 2005), the swimming crab *Portunus trituberculatus* (Liu *et al.*, 2012) and the marine bivalve genus *Mesoderma* (Marins and Levey, 1999) to name but a few, due to the fact that they are ubiquitous elements of eukaryotic genomes (Lado-Insua *et al.*, 2011); and have high variability, abundance, neutrality, co-dominance and unambiguous scoring of alleles (Li *et al.*, 2006; Salgueiro *et al.*, 2003).

Overview of Modiolus modiolus Larval Distribution

As previously mentioned, study of larval distribution is problematic, and as such, study on the larval distribution of *M. modiolus* is limited as a result, in addition to the difficulty in differentiating between mytilid mussel planktonic larvae (Flyachinskaya and Naumov, 2003; Lutz and Hidu, 1979). Work carried out as part of the Strangford Lough Restoration Project (Roberts *et al.*, 2011) also indicated problems with monitoring *M. modiolus* larvae in the field, although the life cycle was successfully described in full through the pilot hatchery, unfortunately very few larvae developed to the pediveliger[‡‡] stage (Roberts *et al.*, 2011). Roberts *et al.* (2011) also indicated that genetic work would need to be carried out to determine whether populations are influenced by an influx of genetic material from outside the partially enclosed Lough and whether this would ultimately have an impact on restoration of the beds. A summary of the Strangford Lough case study is provided in Appendix C.

Oceanic Processes

At a broad scale (Figure 7.2) it is suggested that the general circulation of water around Scotland (and the northern half of the UK is in a northerly direction particularly noticeable on the west coast, although this is subject to seasonal variation. Most water from the North Atlantic enters the North Sea between Orkney and Shetland, with shelf water moving north through the North Channel of the Irish Sea (Marine Scotland, 2011). Although in reality, the patterns of circulation are more complicated, especially in smaller bodies of water such as the Irish Sea (Figure 7.3). The direction of water movement ultimately influences the direction of larval dispersal and the possibility for connectivity.

[‡‡] Planktonic stage that possess a velum (locomotory and feeding organ provided with cilia) and approximately 230-460 µm in size.

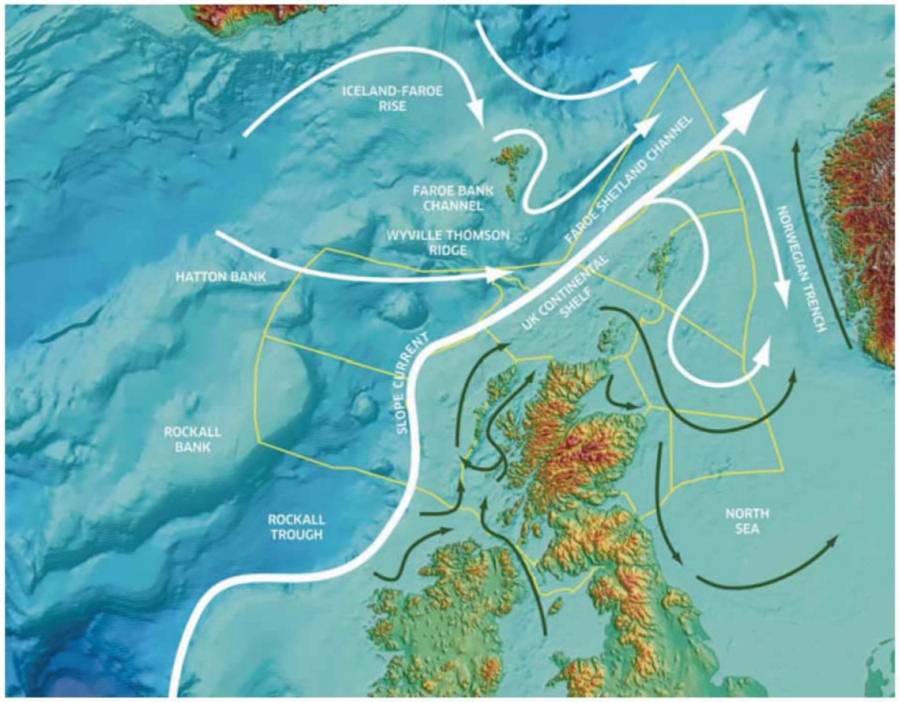


Figure 7.2: Oceanic Processes around northern UK

Source: (Marine Scotland, 2011)

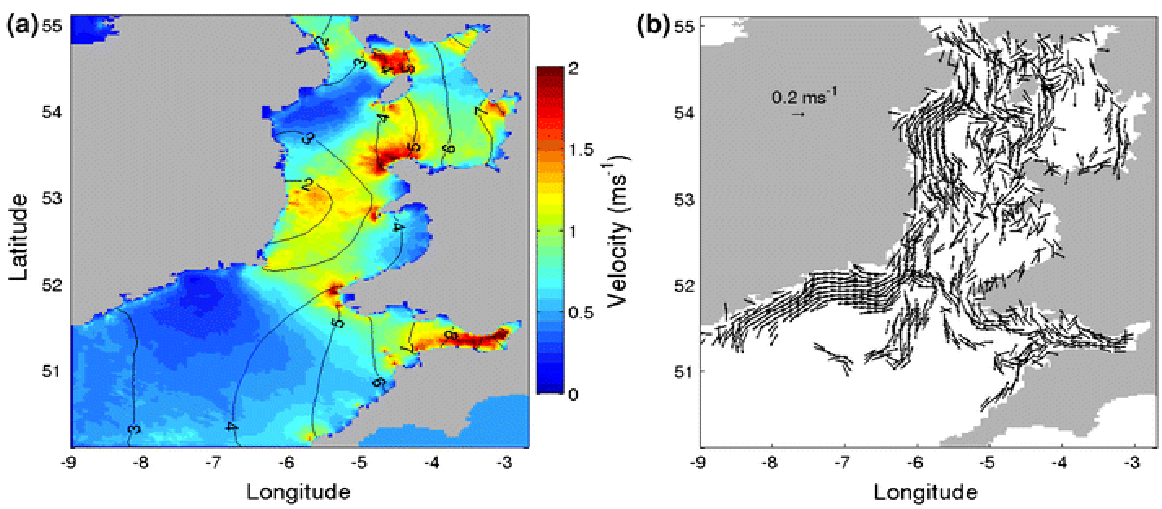


Figure 7.3: (a) Co-tidal contours of maximum tidal range (m) during the 1990 hydrodynamic simulation, superimposed upon coloured contours of maximum depth-averaged scalar velocity (m s-1). (b) Depth averaged residual currents

Source: (Coscia *et al.*, 2013)

7.2 *Modiolus modiolus* phylogeography

7.2.1 Introduction

Halanych *et al.* (2013) carried out an investigation of the intraspecific genetic patterns of *M. modiolus* using partial mitochondrial gene cytochrome oxidase subunit 1 (CO1) data from several localities in the North-East Atlantic and one in the North-East Pacific. Their results showed than the *M. modiolus* samples from the North-East Pacific and the North Atlantic were genetically distinct, forming two separate clades (Halanych *et al.*, 2013). These results indicated that the population collected from the Pacific has considerably higher haplotype and nucleotide diversity compared to the Atlantic populations, suggesting a more recent origin for the Atlantic populations (<50 KYA; 132 KYA for the Pacific population). However, given that only one population was sampled from the Pacific – this diversity may be underestimated. Here, we wanted to examine whether any inferred clustering using the CO1 gene exists within the population around the UK.

7.2.2 Methods: Sample preparation

Extracted DNA (see Section 7.4) for the individuals for each population outlined in Table 7.1 were quantified (see Section 7.4.3) and prepared for PCR reaction.

The PCR reactions were prepared using Illustra PureTaq Ready to Go PCR beads in a final reaction volume of 25µl with 50ng of starting DNA. The cytochrome oxidase subunit 1 (CO1) gene was amplified using the LCO 1490/HCO 2198 primer set (Folmer *et al.*, 1994; Halanych *et al.*, 2013). The following components were included:

- 5 µl DNA sample (Table 7.1)
- 1 µl HCO primer
- 1 µl LCO primer
- 18 µl HPLC water

The PCR beads comprise, taq-polymerase, MgCl and reaction buffer.

PCR reactions were run at 95^{o}C for 3 mins followed by 40 cycles of (94^{o}C for 30 s, 45^{o}C for 30 s, 72^{o}C for 1 min) and ended with a single extension step at 72^{o}C for 10 mins. Completed PCR reaction amplicons were tested on a 1% agarose gel (electrophoresis) to determine presence and quality.

Table 7.1: Sample locations for *Modiolus modiolus* populations, COI screening

Location	Region	No. of Samples
Point of Ayre	Isle of Man	5
Calback Ness	Shetland	5
Karlsruhe	Orkney	5
North Llyn	Wales	5
Strangord	Northern Ireland	5
Port Apin	West of Scotland	5
Ards	Northern Ireland	5

PCR Clean-up

Samples indicating bands on the agarose gel were showed successfully amplified products and these were taken forward for genotyping. Sample cleaning was required in order to remove any primers, dNTPs, salts and other unwanted products from the PCR procedure.

PureLink PCR Purification kits were used (Invitrogen). This clean-up procedure involves 3 steps: Binding, Washing and Eluting of the DNA. Following gel testing of the PCR product, 20 µl remained. The samples were made up to 50 µl by adding 30 µl of HPLC water to the remaining sample.

The following process was then carried out:

- Binding DNA
    - 200 µl of Binding buffer (with added isopropanol) added to the 25 µl volume PCR product
    - Prepared sample pipetted into the provided spin column and collection tube
    - Sample centrifuged at room temperature at 10,000 x g for 1 minute
    - Flow through discarded
- Washing DNA
    - 650 µl Wash buffer (with added ethanol) added to the spin column
    - Centrifuged at 10,000 rpm for 1 minute
    - Flow through discarded
    - Centrifuged for a second time at 14,000 rpm at room temperature for 2- 3 minutes
    - Flow through and collection tube discarded

- Eluting DNA
    - Spin column placed in 1.7ml PureLink elution tube
    - 50 µl Elution buffer added to spin column
    - Incubate for 1 minute at room temperature
    - Centrifuged at 14,000 rpm for 2 minutes
    - Spin column discared and flow through (eluted DNA) stored at -20^{o}C

Sequencing Preparation

A sequence reaction mix was set up using the cleaned PCR products (eluted DNA). A 6 µl volume was required comprising 1 µl 3pmol/ml LCO primer, 2 µl eluted DNA and 3 µl HPLC water. This preparation was repeated with the reverse (HCO) primer again at a concentration of 3pmol/ml

Samples were prepared in thin-walled tubes supplied by the GenePool sequencing facility, Edinburgh (http://genepool.bio.ed.ac.uk/) and samples then sent forward to them for Sanger sequencing analysis. Addition of 'BigDye' to the samples and cycle sequencing reactions were conducted by staff at the GenePool.

7.2.3 Methods: Data Analysis

GenePool sequences were imported and aligned in MEGA 5.2 (Tamura *et al.*, 2011) with Clustal W implementation (Thompson *et al.*, 1994), and confirmed by eye. The aligned data set was assessed through a GenBank Blast search to confirm species identity. The aligned data was combined with CO1 sequence data provided directly from Halanych *et al.* (2013) through personal communication.

Analysis for Model Selection (ML) was carried out to assess which model should be used to construct the maximum likelihood tree. The identified model was selected within the tree builder and 500 bootstrap replications were set.

7.2.4 Results: Maximum Likelihood Tree

The Tamura-Nei 93 model with invariant sites model was concluded as best fit and results from the phylogeny maximum likelihood tree are shown in Figure 7.4. The tree shows two distinct clades Pacific and Atlantic, as described by Halanych *et al.* (2013). Bootstrap analysis with 500 iterations revealed that both the Pacific and Atlantic clades are well-supported, although there is no evidence for population sub-structure within the Atlantic clade.

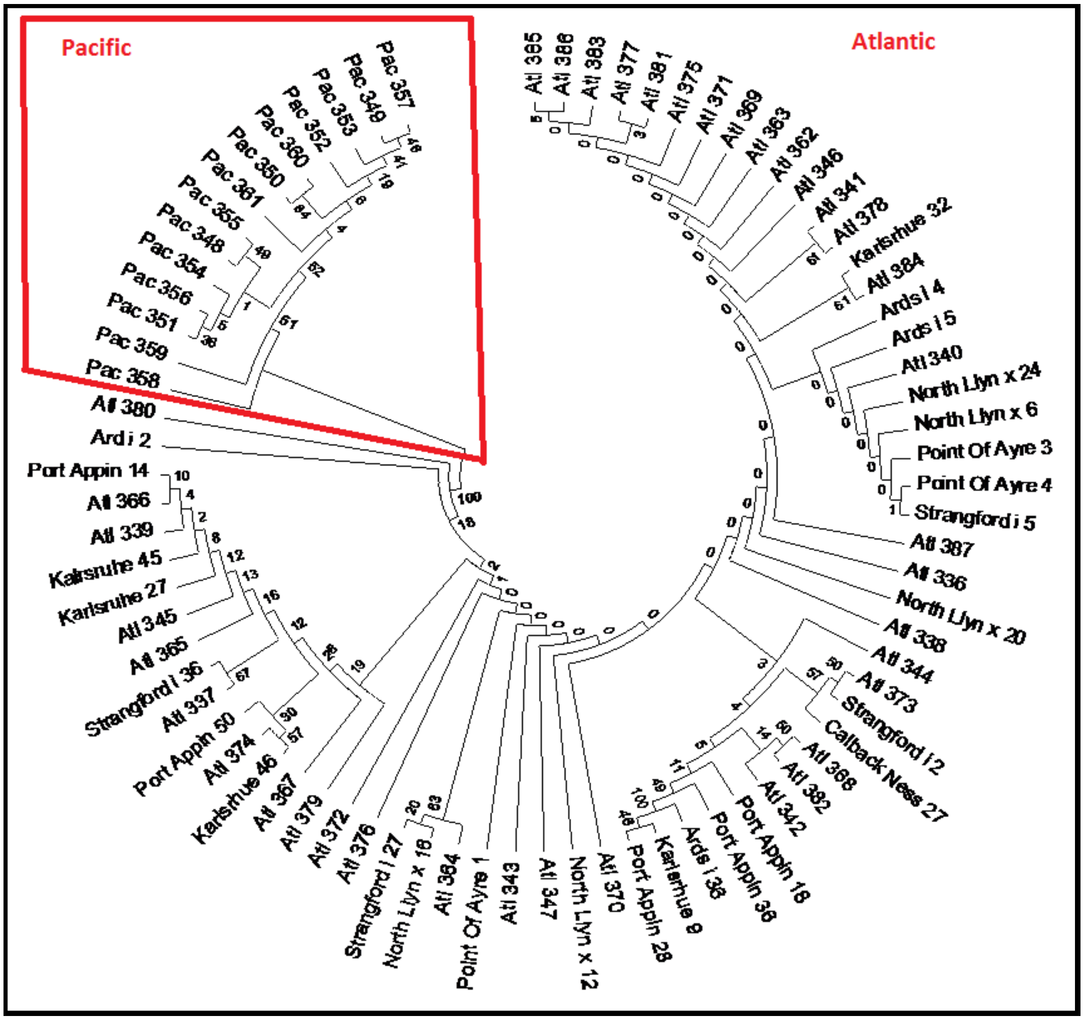


Figure 7.4: Maximum likelihood tree *Modiolus modiolus* CO1, Pacific and Atlantic Ocean populations

7.3 Primer Design and Optimisation

7.3.1 Introduction

Several molecular markers have been developed over the years to describe genetic polymorphisms in various marine mussel species, however, the majority of them have a number of disadvantages for use as population markers, whereas species specific microsatellites are thought to be much more informative (Presa *et al*., 2002). A number of studies on the development and use of microsatellite markers for bivalve molluscs have been conducted, and a sample of these (not a full representation) is shown in Table 7.2.

From a literature review of available markers, it was concluded that no markers have been previously developed for *M. modiolus.*

Table 7.2: Bivalve mollusc microsatellite marker studies

Species	Location	No. populations	No. markers	No. Alleles per marker	Reference
Mytilus galloprovincialis Lamarck, 1819	Spain	5	6	3 to 25	(Diz and Presa, 2009)
Cerastoderma edule (Linnaeus, 1758)	Spain	6	9	11 to 51	(Chust *et al*., 2013)
Cerastoderma edule	UK/ Ireland	8	12	8 to 10	(Coscia *et al*., 2013)
Crassostrea gigas (Thunberg, 1793)	China	5	7	12 to 32	(Li *et al*., 2006)
Hyriopsis cumingii (Lea, 1852)	China	6	8	2 to 25	(Li *et al*., 2009)
Chlamys nobilis Reeve 1852	China	4	5	3 to 12	(Wang *et al*., 2013)
Perna canaliculus (Gmelin, 1791)	New Zealand	-	10	-	(MacAvoy *et al*., 2008)

7.3.2 Methods: Microsatellite Isolation

Microsatellite isolation of *M. modiolus* was carried out by University of Aberdeen from tissue samples prepared by Jones (2011). These samples had been collected from Loch Creran, Scotland and were processed by Jones (2011) following the methodology outlined in Section 7.3.3. Microsatellite isolation was carried out as per the methodologies described by Zane *et al.* (2002). This procedure involved the use of restriction enzymes to fragment the genomic DNA. These DNA fragments were then ligated into a common plasmid vector using ligase and specific adaptors. The recombinant plasmids were transformed into bacterial cells, producing clones of the recombinant plasmid. Screening of the bacterial colonies was carried out to ensure collection of recombinant plasmid. The screened cells were transferred onto 2 x 96 well plates (plate S1 and S2) for subsequent screening and primer design.

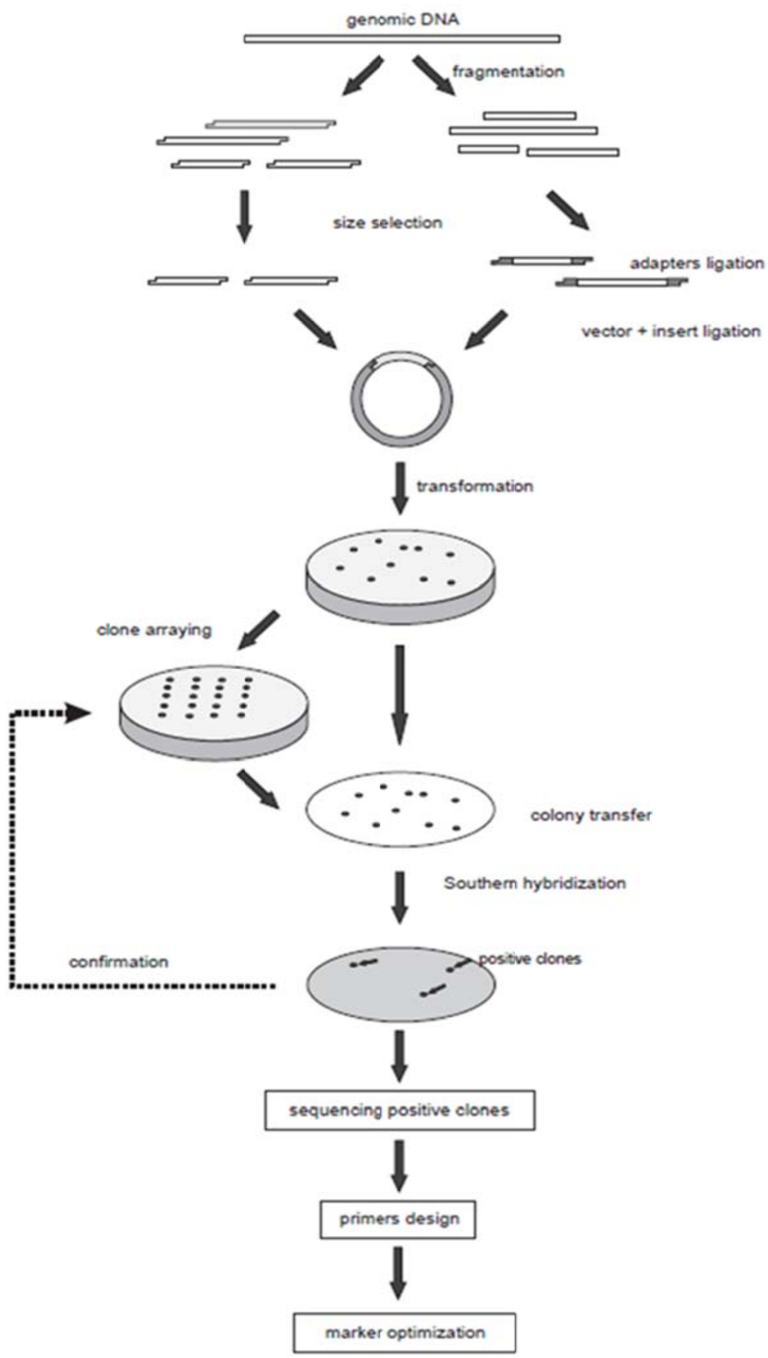


Figure 7.5: Microsatellite Isolation Methodology

Source: (Zane *et al.*, 2002)

7.3.3 Methods: Polymerase Chain Reaction of Clones

The following PCR methodology was applied to plate S2 during this study and carried out by Jones (2011) on plate S1.

Each clone from plate S2 was amplified using PCR methodology using SP6 and T7 vector primers. The PCR reactions were prepared using Illustra PureTaq Ready-To-Go PCR beads in a final reaction volume of 25µl (50ng of starting genomic DNA). The following components were included:

- 5 µl DNA sample (plate S2)
- 1 µl SP6 primer
- 1 µl T7 primer
- 18 µl HPLC water

PCR reactions were run at 94°C for 5 mins followed by 30 cycles of (94°C for 30 s, 55°C for 30 s, 72°C for 30 s) and ended with a single step at 72°C for 10 mins.

PCR amplicons were tested on a 1% Ethidium Bromide agarose gel (electrophoresis) to determine amplification. Gels were made to the following specifications:

- 50ml 0.5 x TBE buffer
- 0.5g agarose
- 3 µl Ethidium Bromide

The gel was placed in 0.5 x TBE buffer and the wells filled with a pre-mixed sample which consisted of 5 µl of PCR product and 2 µl 6 x loading buffer. A 100bp marker (1 µl marker, 2 µl loading buffer and 4 µl HPLC water) was loaded onto the gel. Gels were left to run for 20 mins at 100 mAmps and viewed on a UV light box.

7.3.4 Methods: Initial Primer Design and Preparation

Sequences supplied by The GenePool were downloaded from the GeneSifter web portal and input into a Sequencher (GeneCodes Ltd) project. The sequences were assembled automatically. Consensus sequences were generated from the successfully assembled contigs (see Appendix F).

Sequences were then examined for microsatellite repeat sections. Repeat sections were determined as containing a reasonably sized repeat (minimum 6 repeats) and containing a suitable length of flanking region, which could be used to design primers.

Primers were designed using the Websat portal (Martins *et al.*, 2009). The text sequences exported from Sequencer were uploaded to Websat. The repeat region was highlighted (if present) and the primers were designed based on the available repeat and the corresponding flanking regions.

The primer sequences (forward and reverse) were exported to excel (Appendix F) and ordered from Eurofins MWG Operon. Primers were received in dried form and were made up with the required volume of HPLC grade water to achieve a concentration of 100pmol/µl. These volumes were supplied in the Oligonucleotide Synthesis Report and varied between 250 and 393µl depending on the primer.

The prepared primers (100pmol/µl) were diluted to a 10 x concentration (10µl primer + 90µl HPLC water).

7.3.5 Methods: Primer Optimisation

From the above design steps 34 microsatellite loci (primer pairs) were identified from the initial 192 clones. Primer optimisation was therefore needed to be carried out on each of the 34 primer pairs in order to test for primer suitability, functionality and optimum PCR conditions.

The primer pairs were tested at varying annealing temperatures between 53^{o}C and 58.1^{o}C using two individual *M. modiolus* samples (DNA extracted as per Section 7.4). The individual samples were chosen based on their geographical location, as the two furthest samples populations at the time of testing (Karlsruhe, Orkney and North Llyn, Wales; see Figure 7.8).

The PCR reactions were prepared using Illustra PureTaq Ready-To-Go PCR beads in a final reaction volume of 25µl (50ng of starting DNA) as follows:

- 5 µl DNA sample (Karlsruhe; 284.6ng/µl or North Llyn; 231.7ng/µl)
- 1 µl Forward primer
- 1 µl Reverse primer
- 18 µl HPLC water

A full set of utilised primer pairs are outlined in Table 7.5.

PCR reactions were run on a G-Storm (KAPA BIOSYSTEMS) thermocycler at 94^{o}C for 5 mins followed by 30 cycles of denaturation at 94^{o}C for 30 s; annealing at a gradient temperature from 53^{o}C to 58.1^{o}C for 30 s; elongation at 72^{o}C for 30 s) and ended with a single step at 72^{o}C for 5 mins.

The details of the annealing step are shown in Table 7.3. The primers were tested on samples from Karlsruhe, Scapa Flow (sample A) and North Llyn, Wales (sample B). Tests were run on two samples from different locations to exclude the possibilities that mutations in the annealing region would stop the primers from binding. The testing outline is show in Table 7.3. DNA samples were quantified as per Section 7.4.3.

The final PCR product was run on a 1% agarose gel to check for amplification and determine product size against a 100bp DNA ladder.

The PCR products were run on a 1% agarose gel to determine whether there was any amplification of a product (band present) or not (no band present or smear indicating poor binding of primers). Of the amplicons that were classified as working, they were determined to be either homozygous (single band) or heterozygous (two bands) (Figure 7.6).

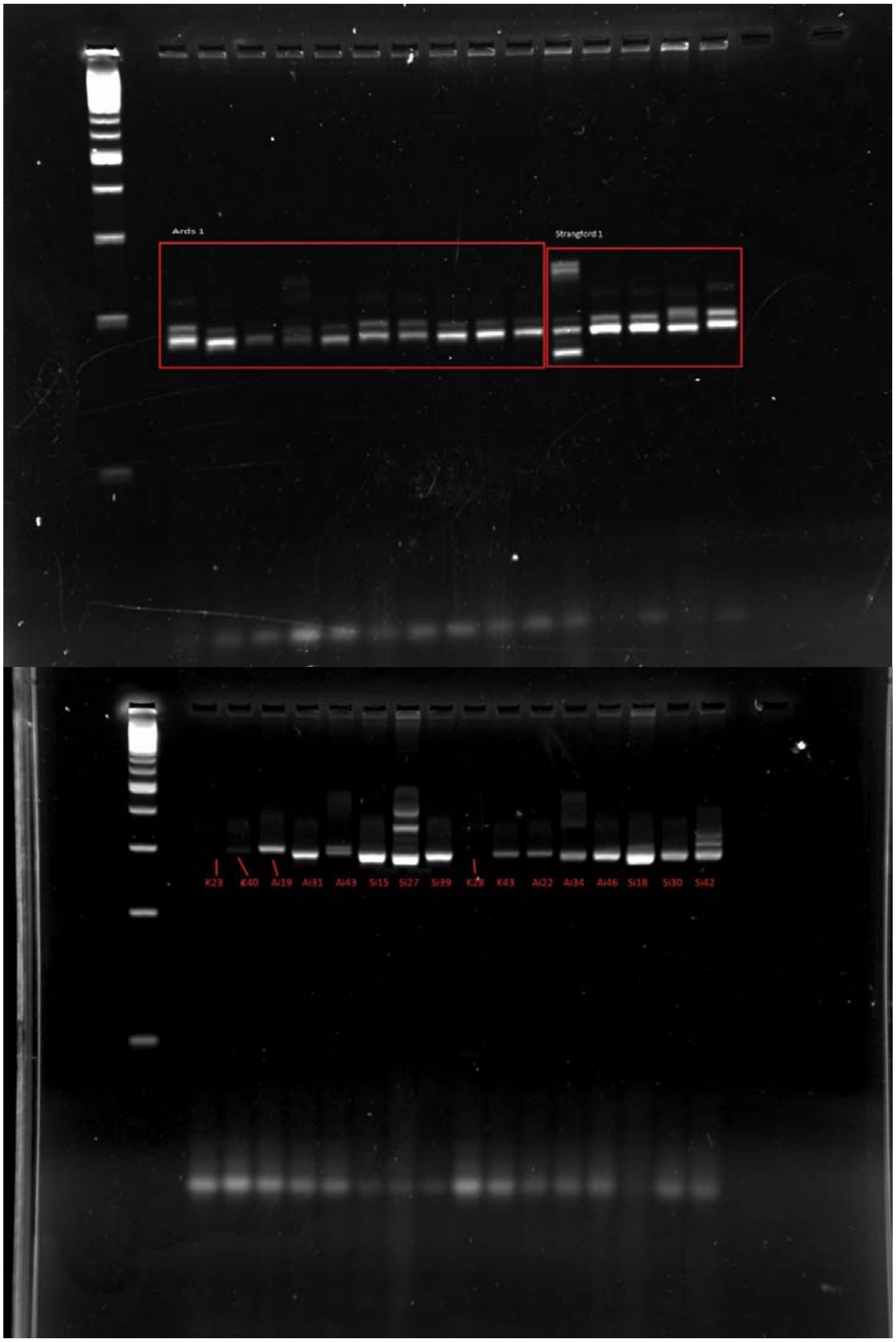


Figure 7.6: Example of primer testing and amplification confirmation on gel

Table 7.3: Temperature Gradient Primer Optimisation Testing Outline.

11/07/2012	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
A	1A	2A	1A	2A	1A	2A	1A	2A	1A	2A	1A	2A
B	1B	2B	1B	2B	1B	2B	1B	2B	1B	2B	1B	2B
C	3A	4A	3A	4A	3A	4A	3A	4A	3A	4A	3A	4A
D	3B	4B	3B	4B	3B	4B	3B	4B	3B	4B	3B	4B
E	5A	6A	5A	6A	5A	6A	5A	6A	5A	6A	5A	6A
F	5B	6B	5B	6B	5B	6B	5B	6B	5B	6B	5B	6B
G	7A	8A	7A	8A	7A	8A	7A	8A	7A	8A	7A	8A
H	7B	8B	7B	8B	7B	8B	7B	8B	7B	8B	7B	8B
19/07/2012	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
A	9A	10A	9A	10A	9A	10A	9A	10A	9A	10A	9A	10A
B	9B	10B	9B	10B	9B	10B	9B	10B	9B	10B	9B	10B
C	11A	12A	11A	12A	11A	12A	11A	12A	11A	12A	11A	12A
D	11B	12B	11B	12B	11B	12B	11B	12B	11B	12B	11B	12B
E	13A	14A	13A	14A	13A	14A	13A	14A	13A	14A	13A	14A
F	13B	14B	13B	14B	13B	14B	13B	14B	13B	14B	13B	14B
G												
H												
01/10/2012	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
A	15A	16A	15A	16A	15A	16A	15A	16A	15A	16A	15A	16A
B	15B	16B	15B	16B	15B	16B	15B	16B	15B	16B	15B	16B
C	17A	18A	17A	18A	17A	18A	17A	18A	17A	18A	17A	18A
D	17B	18B	17B	18B	17B	18B	17B	18B	17B	18B	17B	18B
E	19A	20A	19A	20A	19A	20A	19A	20A	19A	20A	19A	20A
F	19B	20B	19B	20B	19B	20B	19B	20B	19B	20B	19B	20B
G	21A	22A	21A	22A	21A	22A	21A	22A	21A	22A	21A	22A
H	21B	22B	21B	22B	21B	22B	21B	22B	21B	22B	21B	22B
05/10/2012	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
A	23A	24A	23A	24A	23A	24A	23A	24A	23A	24A	23A	24A
B	23B	24B	23B	24B	23B	24B	23B	24B	23B	24B	23B	24B
C	25A	26A	25A	26A	25A	26A	25A	26A	25A	26A	25A	26A
D	25B	26B	25B	26B	25B	26B	25B	26B	25B	26B	25B	26B
E	27A	28A	27A	28A	27A	28A	27A	28A	27A	28A	27A	28A
F	27B	28B	27B	28B	27B	28B	27B	28B	27B	28B	27B	28B
G	29A	30A	29A	30A	29A	30A	29A	30A	29A	30A	29A	30A
H	29B	30B	29B	30B	29B	30B	29B	30B	29B	30B	29B	30B
08/10/2012	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
A	31A	32A	31A	32A	31A	32A	31A	32A	31A	32A	31A	32A
B	31B	32B	31B	32B	31B	32B	31B	32B	31B	32B	31B	32B
C	33A	34A	33A	34A	33A	34A	33A	34A	33A	34A	33A	34A
D	33B	34B	33B	34B	33B	34B	33B	34B	33B	34B	33B	34B
E												
F												
G												
H												
Annealing Temperature (^{o}C) — **Achieved**	**53.0**	**53.2**	**53.5**	**53.9**	**54.5**	**55.1**	**55.8**	**56.5**	**57.2**	**57.7**	**57.9**	**58.1**
Target	**53**		**54**		**55**		**56**		**57**		**58**	

7.3.6 Methods: Primer Selection and Labelling

Primer pairs that were considered to produce products that were heterozygous were selected for further analysis. A total of 14 primer pairs were thought to produce heterozygotes. In addition, 2 primer pairs thought to be homozygous were also selected in order to provide a positive comparative assessment. The forward primers for these loci were labelled with a "FAM" fluorescence tag and PCR was carried out against 1 individual *M. modiolus* sample from 4 of the different *M. modiolus* populations (Table 7.6). The PCR products were initially run on a 1% agarose gel to double check that the amplification worked prior to progression onto the Fragment Size Analysis.

7.3.7 Methods: Fragment Analysis

Fragment Size Analysis (FSA) was carried out by Dundee University. The PCR fragments were run alongside a ROX500 size standard in an ABI 3130 Genetic Analyser and alleles were scored using Genemapper version 3.5. Scored peak graph images were received and the peaks determined as representing the correct alleles were tabulated (e.g. Figure 7.7). These peaks were confirmed based on the results of the Acrylamide gel runs (Figure 7.6). As a number of the primers were not working clearly, areas considered erroneous were not scored (e.g. areas of stutter, smearing or shadowing; artefacts). The largest peaks were compared with those produced on the acrylamide gel and were considered to represent the alleles.

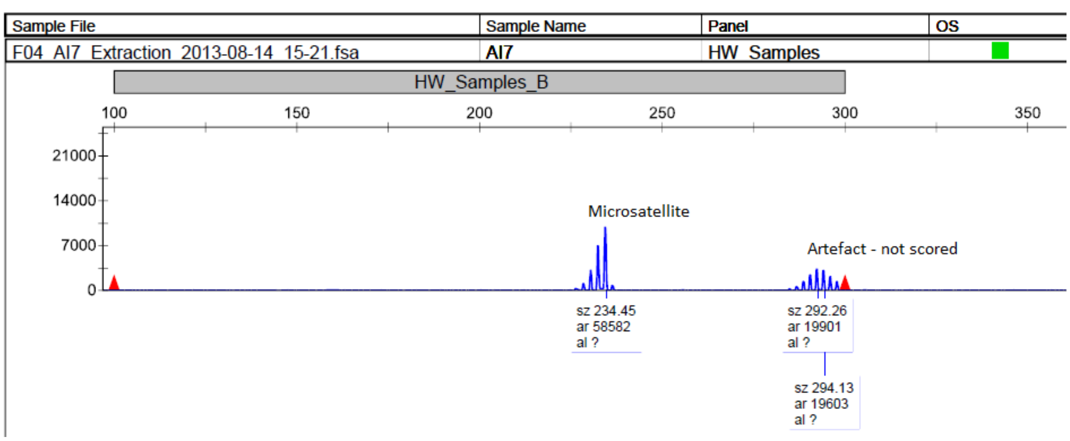


Figure 7.7: Example of Genemapper v3.5 FSA output

7.3.8 Results: Selected Primers

Table 7.4 shows the results from the primer optimisation testing. The temperature gradient ranged from 53.0^{o}C to 58.1^{o}C. Following testing of the products on the agarose gel, the table was colour coded in order to show which loci were present or not. From initial testing, generally, all 'working' primers worked well across the temperature gradient.

The primer pairs that were considered to be working against the DNA samples from the two locations were then classified as being heterozygous (double band) or Homozygous (single band) through examination on the agarose or acrylamide gels. The details of the primer pairs are outlined in Table 7.5. At this stage of testing development of heterozygous loci was of primary interest. The primer pairs that were ascertained to have heterozygous samples are highlighted yellow. Fluorescently labelled forward primers for these loci were then ordered from Eurofins (FAM and HEX) and Applied Biosystems (NED). The labels and the corresponding loci are as follows:

- NED (yellow/black): 10, 12, 20, 25, 32
- HEX (green): 6, 11, 13, 22
- FAM (blue): 2, 9, 26, 15, 17, 30, 33

The 14 of the 16 loci run against 1 individual from 4 populations was sent to Dundee University for initial FSA. Primers 22 and 25 were not taken forward as they were showing smearing on the agarose gel and amplification was considered to be of poor quality at time of testing.

The peak scored graphs (Figure 7.7) were received and the scored alleles are shown in Table 7.6. Particular issues were encountered through the FSA, particularly the presence of multiple peaks rather than the expected one (Homozygous) or two (Heterozygous). It was thought that *M. modiolus* might be a triploid organism, which might have explained some of the additional peaks. However, previous studies showed that it is likely that it is in fact a diploid organism (Thiriot-Quievreux, 2002). Although no specific data are available for *M. modiolus*, similar bivalve species are reported as diploid, therefore in this study it is assumed that *M. modiolus* is too.

Table 7.4: Temperature Gradient Primer Optimisation: Testing Results

11/07/2012	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
A	1A	2A	1A	2A	1A	2A	1A	2A	1A	2A	1A	2A
B	1B	2B	1B	2B	1B	2B	1B	2B	1B	2B	1B	2B
C	3A	4A	3A	4A	3A	4A	3A	4A	3A	4A	3A	4A
D	3B	4B	3B	4B	3B	4B	3B	4B	3B	4B	3B	4B
E	5A	6A	5A	6A	5A	6A	5A	6A	5A	6A	5A	6A
F	5B	6B	5B	6B	5B	6B	5B	6B	5B	6B	5B	6B
G	7A	8A	7A	8A	7A	8A	7A	8A	7A	8A	7A	8A
H	7B	8B	7B	8B	7B	8B	7B	8B	7B	8B	7B	8B
19/07/2012	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
A	9A	10A	9A	10A	9A	10A	9A	10A	9A	10A	9A	10A
B	9B	10B	9B	10B	9B	10B	9B	10B	9B	10B	9B	10B
C	11A	12A	11A	12A	11A	12A	11A	12A	11A	12A	11A	12A
D	11B	12B	11B	12B	11B	12B	11B	12B	11B	12B	11B	12B
E	13A	14A	13A	14A	13A	14A	13A	14A	13A	14A	13A	14A
F	13B	14B	13B	14B	13B	14B	13B	14B	13B	14B	13B	14B
G												
H												
01/10/2012	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
A	15A	16A	15A	16A	15A	16A	15A	16A	15A	16A	15A	16A
B	15B	16B	15B	16B	15B	16B	15B	16B	15B	16B	15B	16B
C	17A	18A	17A	18A	17A	18A	17A	18A	17A	18A	17A	18A
D	17B	18B	17B	18B	17B	18B	17B	18B	17B	18B	17B	18B
E	19A	20A	19A	20A	19A	20A	19A	20A	19A	20A	19A	20A
F	19B	20B	19B	20B	19B	20B	19B	20B	19B	20B	19B	20B
G	21A	22A	21A	22A	21A	22A	21A	22A	21A	22A	21A	22A
H	21B	22B	21B	22B	21B	22B	21B	22B	21B	22B	21B	22B
05/10/2012	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
A	23A	24A	23A	24A	23A	24A	23A	24A	23A	24A	23A	24A
B	23B	24B	23B	24B	23B	24B	23B	24B	23B	24B	23B	24B
C	25A	26A	25A	26A	25A	26A	25A	26A	25A	26A	25A	26A
D	25B	26B	25B	26B	25B	26B	25B	26B	25B	26B	25B	26B
E	27A	28A	27A	28A	27A	28A	27A	28A	27A	28A	27A	28A
F	27B	28B	27B	28B	27B	28B	27B	28B	27B	28B	27B	28B
G	29A	30A	29A	30A	29A	30A	29A	30A	29A	30A	29A	30A
H	29B	30B	29B	30B	29B	30B	29B	30B	29B	30B	29B	30B
08/10/2012	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
A	31A	32A	31A	32A	31A	32A	31A	32A	31A	32A	31A	32A
B	31B	32B	31B	32B	31B	32B	31B	32B	31B	32B	31B	32B
C	33A	34A	33A	34A	33A	34A	33A	34A	33A	34A	33A	34A
D	33B	34B	33B	34B	33B	34B	33B	34B	33B	34B	33B	34B
Annealing Temperature (°C)	**53.0**	**53.2**	**53.5**	**53.9**	**54.5**	**55.1**	**55.8**	**56.5**	**57.2**	**57.7**	**57.9**	**58.1**
	53		**54**		**55**		**56**		**57**		**58**	
Key:		Working		Faint		Not Working	A = Karlsruhe sample, B = North Llyn sample					

Table 7.5: Working/Selected Primer Sequences

Name			Sequence (5' >- 3')	Base Pairs	Amplicon bp
Modmicro	1	F	AAGCGTTGTCCCATTGATATGT	22	300
Modmicro	1	R	CATAAAAGTGTGCCCTTGATCC	22	
Modmicro	2	F	CTCCGCTATGTT TGACCATGTA	22	500/300
Modmicro	2	R	TCCACACCGAGTAACAAATCAG	22	
Modmicro	5	F	AAGGTCAAGGTC ACATTGAAGGT	22	300
Modmicro	5	R	TAGAGCTTA TGGCTGCGTTGT	21	
Modimicro	6	F	CAATCAATCACACAACCAGACAGA	24	200/100
Modimicro	6	R	TGGCACGAGCGTTAGCAG	18	
Modimicro	9	F	ACAGCAACTGACCTCCAGATTT	22	300/100
Modimicro	9	R	TTCTTCTTTTCCTTATCCGGTG	22	
Modimicro	10	F	ACATAGCGCGGCAAGTTC	18	400/100
Modimicro	10	R	TTGATCTCATTTCGTGGTTGAG	22	
Modimicro	11	F	AGAATCCTTTCTGTGTTGTCCG	22	400/100
Modimicro	11	R	CATCTGCCTACCTACAGTTCCC	22	
Modimicro	12	F	GGTTCACCACCATGTATGAGC	21	200/100
Modimicro	12	R	GCAGAGTGGGCATCTACAGTTA	22	
Modimicro	13	F	CACAGCCTCCTGGTCACAATA	21	300/100
Modimicro	13	R	TGGCGTGTTATTCTAGCAAATG	22	
Modimicro	14	F	CCACACTCACACACTCACACAC	22	100
Modimicro	14	R	TAGCAGAATCACTACGCTCCAA	22	
Modimicro	15	F	CCATGTGAGATTGATCCTTGAG	22	200
Modimicro	15	R	CCACGCACCTAATGGTTATAGA	22	
Modimicro	16	F	TTCAGAGTAGATTTAGGGTGTGAGG	25	100
Modimicro	16	R	CTAGCAGAATCACGACACATGC	22	
Modimicro	17	F	CGTCCAGTGAGCAGTATTTCAG	22	300
Modimicro	17	R	CATGCAGGATAAAGATCCCTTC	22	
Modimicro	18	F	CTAGCAGAATCCTCGTCCAGAG	22	200
Modimicro	18	R	GTTCAAGATCAGCAGGACCAAG	22	
Modimicro	20	F	AATTGCTCACTTGGCGTAAAAC	22	200/300
Modimicro	20	R	TGGAAATGGAGAGACAGATCCT	22	
Modimicro	21	F	ACACGACTGGTCATCCATACAG	22	200
Modimicro	21	R	AAATCCGTGCAGAATGTCAA	20	
Modimicro	22	F	CATAAAAGTGTGCCCTTGATCC	22	700/300
Modimicro	22	R	AAGCGTTGTCCCATTGATATGT	22	
Modimicro	23	F	CTATTCTGACGACTGACGATGG	22	100 or 200
Modimicro	23	R	CTTATGCCCTTCAACAACAACA	22	
Modimicro	25	F	CATAAAAGTGTGCCCTTGATCC	22	700/300
Modimicro	25	R	AAGCGTTGTCCCATTGATATGT	22	
Modimicro	26	F	TTCAGAGTAGATTTAGGGTGTGAGG	25	200/100
Modimicro	26	R	CTAGCAGAATCACGACACATGC	22	
Modimicro	28	F	CTATTCCACAATTCCAGCCTTC	22	100 or 200
Modimicro	28	R	TGCTGCTCTTGCTCAACATTAC	22	
Modimicro	30	F	CACACAAGACAGGCCAGATAGA	22	700/200
Modimicro	30	R	GAAGAATCCCCACAAACACATT	22	
Modimicro	32	F	CGTTTATTATGTCTCCCCTTCG	22	600/200
Modimicro	32	R	CACCCACATGCGAAATATCTTA	22	
Modimicro	33	F	ATTGATTGGTGTGGGTTTATGC	22	200/100
Modimicro	33	R	TATATGACCGCTGAAAAGACGC	22	

Table 7.6: Initial Fragment Analysis (peak sizes; base paris)

Primer	Initial Specimens tested (peak size; base pairs)															
	Ai1 (Ards i)				K54 (Karlsruhe)				NLiii1 (North Llyn iii)					PA1 (Port Appin)		
Label: NED																
10	344	344			344	344			344	344				344	344	
12	102	102			100	100			100	100				103	103	
20	180	187	211	238	187	194	211	238	180	187	194	211	238	187	211	238
32	133	146	158		133	146	158		146	158				133	146	158
Label: HEX																
6	136	145	224		141	149	228		149	170				139	150	169
11	282	282			349	349			282	282				282	282	
13	183	183			200	200			181	181				181	191	
Label: FAM																
2	-	-			218	225			227	251				227	251	
9	208	239	251		208	239	251		208	239	251			208	242	254
15	181	196	202		181	190	198		181	190	197			181	193	196
17	228	243			228	242			230	243				230	243	
26	99	127	194		99	99			99	99				-	-	
30	172	172			158	174			181	190	196			172	172	
33	138	172			137	172			138	172				138	172	

Although 24 microsatellite markers had been isolated and 14 characterized, not all of them worked well in the 4 populations selected for testing. Unfortunately, it was not possible to proceed with the full suite of 14 loci for full population analysis at this stage. Therefore, at time of testing, it was necessary to select only the loci that showed variation between the populations (i.e. ones that were considered to not be homozygous for the same allele for all populations tested) and the best quality peaks. Therefore, primers 10, 12, 15, 17, 20 and 32 were excluded from further testing at this stage due to a lack of variation.

Issues that arose from the initial scored peaks (messy peaks, off the scale peaks) resulted in further primer optimisation. Therefore, the DNA for two populations (Ards i and Karlsruhe) was re-quantified, and the PCR reaction was tested against DNA concentrations of 1ng/µl, 10ng/µl and 20ng/µl (50ng/µl was the standard) at both 57 and 59^{o}C. The scored peaks were analysed and it was concluded that optimised conditions were set at 59^{o}C and a concentration of 20ng/µl.

Following this additional testing, a number of primers were still deemed as not working properly; therefore primers 6, 9, 26 and 33 were excluded from further testing at this stage.

It was concluded that Primers 2, 11, 13 and 30 provided the best results with regard to the FSA and were therefore selected for further population screening.

7.4 Microsatellite Population Screening

7.4.1 Methods: Field Collection

Samples of *Modiolus modiolus* were collected by SCUBA diver hand collection from the following sites listed in Table 7.7 and illustrated in Figure 7.8.

Collected samples were stored in an aquarium tank at 14-15^{o}C in aerated seawater until sample preparation. A 25% tank water change was carried out every 3-4 days to ensure water quality and feed availability.

Table 7.7: *Modiolus modiolus* beds populations sampled (*corresponds with screened population location as shown by the star in Figure 7.8)

Site	Collection Date	Latitude	Longitude	Depth	No. Genetic Samples
Northern Ireland - Other Ards 1*	nd	54.582	-5.457	nd	83
Northern Ireland - Outer Ards 2	nd	54.519	-5.412	nd	62
Northern Ireland – Ards 2012	nd	nd	Nd	nd	nd
Northern Ireland - Strangford Lough 1*	06/04/2011	-5.594	54.454	24.9m	57
Northern Ireland - Strangford Lough 2	06/04/2011	-5.625	54.417	nd	48
West of Scotland - Oban	26/10/2011	-5.487	56.412	13.2m	49
West of Scotland - Port Appin	04/11/2011	-5.424	56.551	24m	50
Orkney – Karlsruhe*	11/09/2011	-3.190	58.889	nd	60
Orkney - North Cava	05/03/2011	-3.177	58.889	24m	55
South East Risa	09/06/2011	-3.188	58.855	nd	50
North Wales - North Llyn 2010*	23/06/2010	-4.654	52.944	32.7m	50
North Wales - North Llyn 2011 1	12/07/2011	-4.635	52.942	30.7m	51
North Wales - North Llyn 2011 2	13/07/2011	-4.636	52.943	29.9m	51
North Wales - North Llyn 2011 3	14/07/2011	-4.562	53.004	22.9m	50

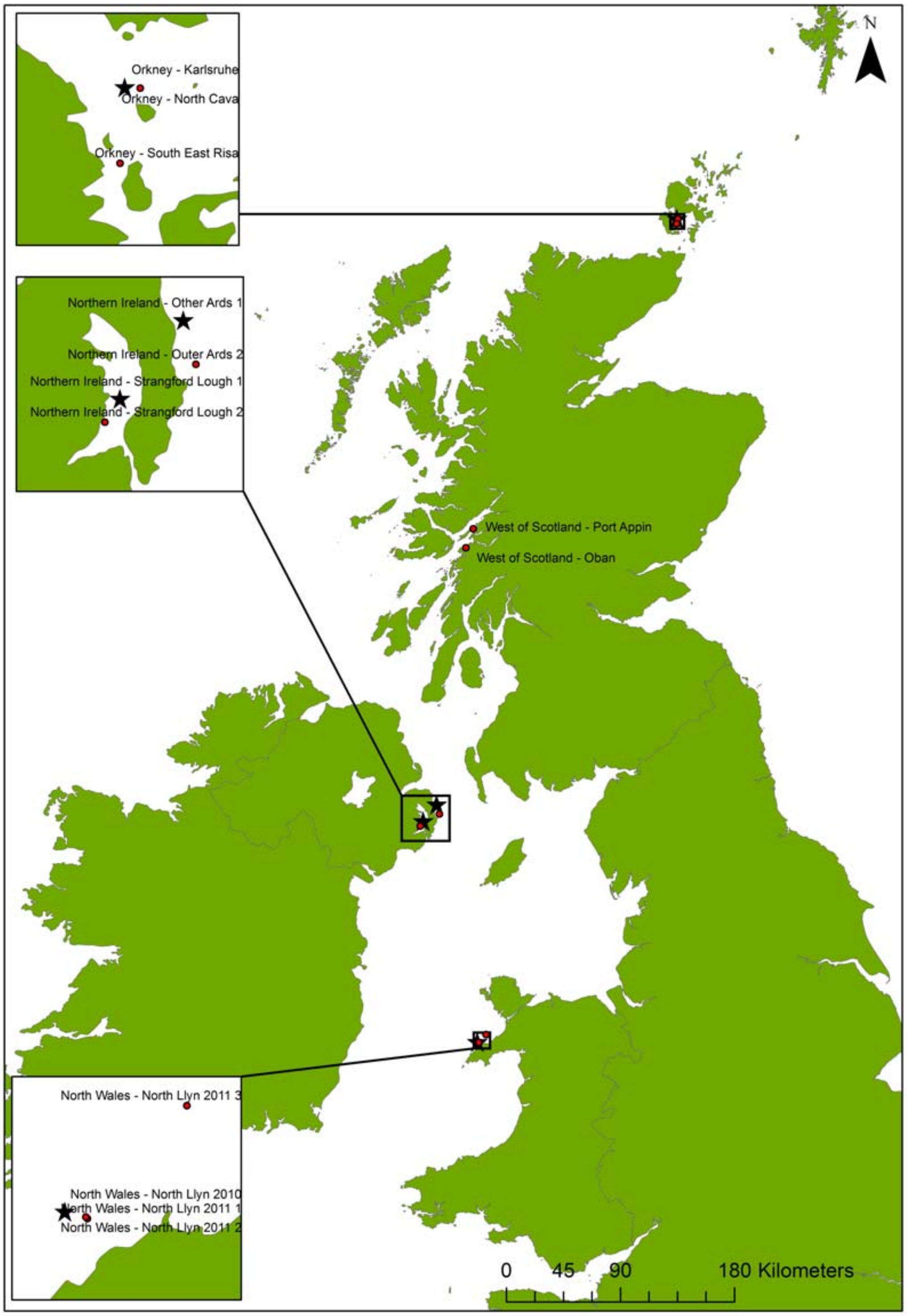


Figure 7.8: ***Modiolus modiolus*** **bed populations**

7.4.2 Methods: Sample Preparation

Samples were measured using digital callipers for overall animal length (A), height (B) and width (C). See Figure 7.9 for details of measurements. Measurements were not required for this study, but will be utilised in conjunction with further studies. In addition, observations of shell damage and/or presence of parasites (pea crabs; *Pinnotheres* sp.) were also recorded and catalogued for separate future study.

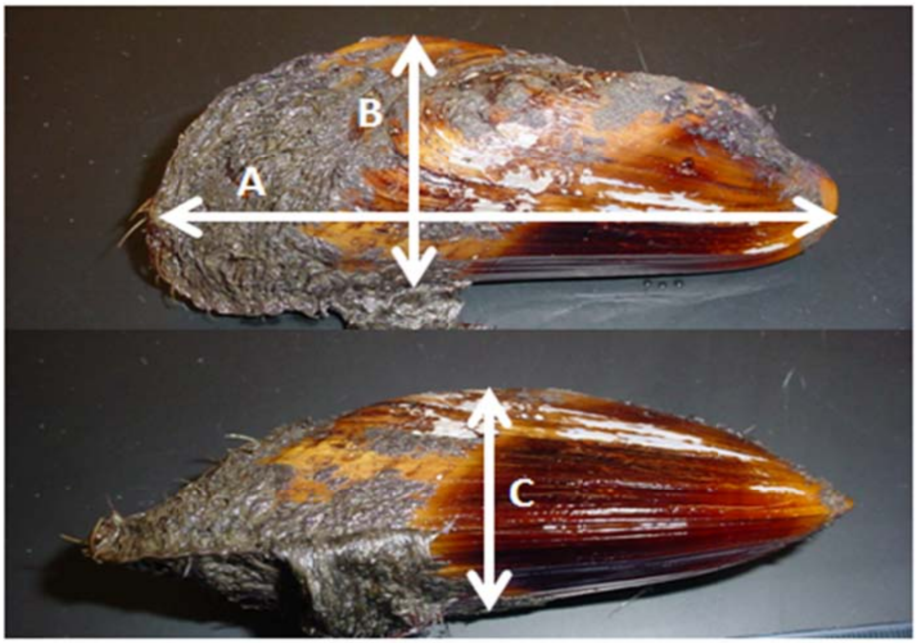


Figure 7.9: Measurement description of mussels: A = Length; B = Height; C = Width

Source: Adapted from Cowles (2005)

Following measurements, mussels were dissected in a manner which caused minimal damage to the mussel's body tissue, due to the requirement of parasitic work. Therefore, extraction of the tissue and adductor muscle was carried out, where possible, in conjunction with the NOAA Technical Memorandum "Histological Techniques for Marine Bivalve Molluscs: Update" (Kim *et al.*, 2006). Unfortunately, shucking of the fresh mussels was required as it was necessary to preserve the adductor muscle in ethanol and not contaminate it with Davidson's fixative as stated in the procedures. Therefore alterations were made to the tissue preparation procedure in order to obtain the required samples while still preserving the tissue for further study.

A scalpel was inserted between the shells at the ventral lip and run dorsally between the shells; the adductor muscle was cut as close the shell as possible and posterior muscle also cut. With the mussel completely open, while still preserving the shell hinge, the adductor muscle was completely removed and placed on a separate cutting surface. The remaining tissue was removed from the shell and placed in a sample jar (size of which varied due to variation in mussel size).

It should be noted that the shells and the remaining body tissue were stored in 4% formalin separately for future ecology and parasitic study, not associated with this project.

The adductor muscle was cut into smaller sections (4-5 depending on size) and stored in 96-100% ethanol in 25ml specimen tubes in preparation for DNA extraction. Samples were stored in an 8^{o}C cold room prior to DNA extraction.

7.4.3 Methods: DNA Extraction

Genomic DNA extraction was carried out using the QIAGEN DNeasy® Blood and Tissue kit protocol (QIAGEN, 2006). The stored samples were removed from the cold room as required. 2ml eppendorf tubes were labelled and 180µl ATL Buffer was added. A small section of the adductor muscle tissue (approximately 2mm^2) was removed from the storage tube and any excess ethanol was allowed to air dry off the tissue. The sample was cut if too large and placed into the buffer solution. The tissue was cut in the eppendorf tube using a pair of scissors until thoroughly homogenised. This process was repeated for all samples.

Following homogenisation of the sample, 20µl of Proteinase-K was added and the samples were mixed on a vortex for a few seconds. The samples were placed on a heating block set at 56^{o}C for at least one hour, or until completely lysed. Samples turned a cream colour compared to the original white upon lysing. The samples were mixed a few times during lysis to ensure the sample was not adhering to the bottom of the tube.

Upon completion of lysis, the samples were mixed on the vortex for 15 seconds. The binding process then followed involving the addition of 200µl AL Buffer and 200µl ethanol. The samples were mixed thoroughly on the vortex immediately upon addition of the buffer, and again immediately after addition of the ethanol. The mixture was pipette into the prepared DNeasy Mini spin column and collecting tube. The column and tube were centrifuged at 8000rpm for 1min. The flow through was discarded and the column placed in a new collection tube.

The washing stage involved the addition of 500µl of Buffer AW1 to the column, and the sample centrifuged at 8000rpm for 1min. The flow-through was discarded and the column placed into a new collection tube. 500µl of Buffer AW2 was added to the column and the sample was centrifuged at 14,000rpm for 3 mins. The flow-through was discarded and the column was placed into a 2ml eppendorf tube.

200µl of Buffer AE was pipette directly onto the membrane of the column and the sample was incubated at room temperature for 1min and centrifuged at 8000rpm for 1min. This process involved the changing of the DNA from its insoluble form to its soluble form. The resulting mixture was then frozen at -20^{o}C awaiting further use.

Confirming DNA Extraction

Upon completion of DNA extraction, the samples were run on a 1% agarose gel (stained with Ethidium Bromide) to check the quality of the genomic DNA, prior to amplification through Polymerase Chain Reaction (PCR) methods (as per Section 7.4.4). A Hind III base pair ladder was used for testing. The presence of a distinct single band indicated successful DNA extraction.

DNA Quantification

Quantification of DNA samples was carried out using a spectrophotometer (Eppendorf). The spectrophotometer was calibrated to zero using 50µl of QIAGEN DNeasy® buffer AE. 5µl of DNA sample and 45µl of HPLC water were prepared and pipetted into the cuvette. The cuvette was placed in the spectrophotometer and the dsDNA reading selected. The DNA concentration (ng/ul) and the 260/280 ratio were recorded. A ratio of 1.1 to 1.8 indicated good quality DNA. The DNA samples were diluted to 50ng/µl if readings were greater than 50ng/µl or multiplied up if below.

7.4.4 Methods: Screening

The microsatellite markers (modimicro 2, 11, 13, and 30) developed and selected in Section 7.3.8 were screened against 4 populations: Ards i (Ai), Strangford i (Si), North Llyn 2010 (NLx) and Karlsruhe (K) (Figure 7.8); following the process outlined below:

- DNA quantification: concentration at 20ng/µl

- PCR amplification – PCR reactions were run at 94^{o}C for 5 mins followed by 30 cycles of (94^{o}C 30 s, 57^{o}C 30 s, 72^{o}C 30 s) and ended with 72^{o}C 5 mins.
- Fragment Size Analysis – see Section 7.3.7
- Scoring and tabulating of FSA peaks – see Section 7.3.8

7.4.5 Methods: Data Analysis

Analysis of data was conducted in part following the methods detailed by Coscia *et al.* (2013), Diz and Presa (2009) and Bell (2008).

Frequencies of null alleles were estimated using FreeNA (Chapuis and Estoup, 2007). Deviations of genotype frequencies from the Hardy-Weinberg equilibrium (HWE) and linkage disequilibrium were tested in GENEPOP 4.0 (Raymond and Rousset, 1995); along with genetic variation assessed through estimation of allelic frequencies, observed (Ho) and expected heterozygosities (He); and used to calculate F_{is} and F_{st} [θ estimator (Weir and Cockerham, 1984)] values. Allelic richness and number of private alleles were calculated using Fstat 2.9.3 (Goudet, 1995) along with F_{st} pairwise test for differentiation (120 permutations).

Analysis of molecular variance (AMOVA) was carried out using Arlequin 3.5 (Excoffier *et al.*, 1992; Excoffier and Lischer, 2010) to estimate genetic diversity within and among populations, and significance was tested against 1000 permutations as per Coscia *et al.* (2013) and Bell (2008).

Finally, population structure was analysed using the Bayesian clustering techniques implemented in the software STRUCTURE 2.3.1 (Pritchard *et al.*, 2000; Chust *et al.*, 2013). STRUCTURE was run allowing for admixture and correlated allele frequencies using 500,000 iterations following a 100,000 burn-in period to ensure chain convergence. STRUCTURE uses individual multilocus genotype data to cluster individuals into groups (k) while minimising Hardy-Weinberg disequilibrium. Δk is a good predictor for the real number of clusters in the data (Chust *et al.*, 2013). The value of k was calculated from analysis of results in STRUCTURE Harvester (Earl and von Holdt, 2012) by averaging the mean posterior probability of the data L(k) over 5 independent runs.

7.4.6 Results: Population Screening

The average number of alleles (including all markers) per population ranged from 13.25 at North Llyn to 21.75 at Strangford Lough and the number of private alleles was greatest at Strangford (28) and least at North Llyn (4). A total number of 117 different alleles, ranging in size from 147 to 349 bp were found at the 4 loci.

The observed heterozygosity was lowest (0.322) in the North Llyn population and highest (0.500) in the Strangford population. Overall, the expected heterozygosity (H_e) ranged from 0.731 (North Llyn) to 0.840 (Strangford) and was significantly higher than the observed heterozygosity (H_o) indicating a possible heterzygote deficiency (Table 7.8).

Table 7.8: Genetic Diversity Parameters inferred from microsatellites

								F_{st} (before and after ENA correction)			
	N	**H_e**	**H_o**	**N_A**	**A_R**	**A_p**	**F_{is}**	**Karlsruhe**	**Ards**	**Strangford**	**North Llyn**
Karlsruhe	48	0.768	0.476	16.25	15.89 ± 8.6	13	**0.369**		0.006	0.023	0.001
Ards	49	0.821	0.434	19.75	19.17 ± 14.2	13	**0.467**	0.006		-0.002	0.018
Strangford	48	0.840	0.500	21.75	20.86 ± 14.3	28	**0.403**	0.022	0.002		0.041
North Llyn	48	0.731	0.322	13.25	13.09 ±10.7	4	**0.538**	0.002	0.013	0.034	

N = number of samples; H_e = Expected Heterozygosity; H_o = Observed Heterozygosity; N_A = number of alleles; A_R = Allelic Richness; N_p = number of Private Alleles; F_{is} = inbreeding coefficient; F_{st} before (upper diagonal) and after (lower diagonal) ENA correction. Significant values in Bold.

Table 7.9: FSTAT Fst (Pairwise test for differentiation)

Population	**F_{st}**			
	Karlsruhe	**Ards**	**Strangford**	**North Llyn**
Karlsruhe		0.067	0.008*	0.042‡
Ards			0.075	0.008*
Strangford				0.008*
North Llyn				

*Indicative adjusted nominal level (5%) for multiple comparisons is: 0.0083 following bonferroni correction

‡'weak' significance (p=0.04)

The presence of null alleles was detected within all 4 markers for all 4 populations tested ($r > 0.05$) and significant positive F_{is} values for all populations indicate a deficiency of heterozygotes compared to that expected under the Hardy-Weinberg Equilibrium (HWE). Therefore it was concluded that all populations were not in Hardy-Weinberg Equilibrium and the significant positive F_{is} values indicates high levels of inbreeding within the populations.

The presence of null alleles within marine bivalves has been discussed by Coscia *et al.* (2013). It has been demonstrated that the inclusion of markers with null alleles can lead to an overestimation of the genetic differentiation (F_{st}). Given that all markers and populations contained null alleles, it was therefore not possible to exclude the null allele markers from the calculations. Therefore, pairwise F_{st} was calculated before and after ENA correction within FreeNA (Chapuis and Estoup, 2007) to allow for the inclusion of all markers.

Pairwise Fst values before ENA correction ranged from -0.002 (Strangford/Ards) to 0.041 (Strangford/North Llyn); and after correction ranged from 0.002 (Strangford/Ards; North Llyn and Karlsruhe) to 0.034 (North Llyn/Stragnford) (Table 7.8). F_{st} values are scored on a scale of 0 to 1 (where 0 = no differentiation between populations and 1 = complete differentiation between populations). The largest potential differentiation was noted between North Llyn and Strangford. Unfortunately significance of differentiation could not be calculated as the software would only allow for bootstrapping on more than 4 markers. Following correction, values remained in the same order of magnitude, indicating that the null alleles were not overly influencing F_{st} estimates.

F_{st} pairwise test for differentiation of all loci (Table 7.9) ranged from 0.008 (Strangford/Karlsruhe, Strangford/North Llyn, Ards/North Llyn) to 0.075 (Ards/Strangford). Significant differentiation was recorded between the Strangford and Karlsruhe, Ards and North Llyn, and Strangford and North Llyn populations, with a low, but significant F_{st} (0.008). The Karlsruhe and North Llyn populations show a 'weak' significant differentiation ($p=0.04$ before Bonferroni correction). The Stangford/Ards and Karlsruhe/Ards populations appear not to be significantly differentiated suggesting that they are genetically similar (Figure 7.10).

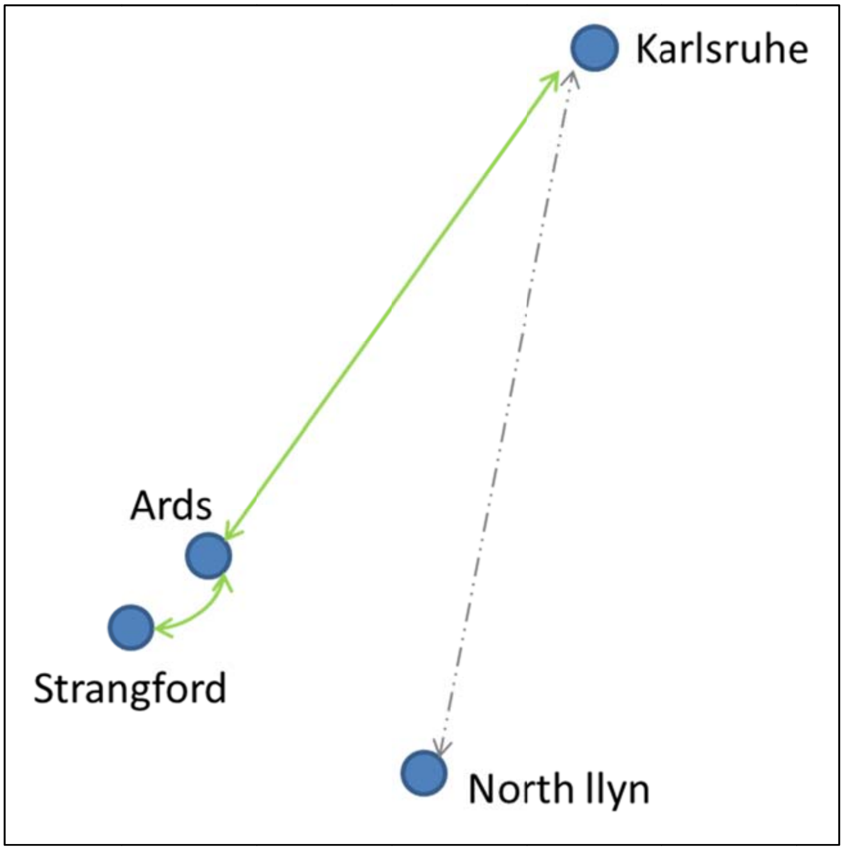
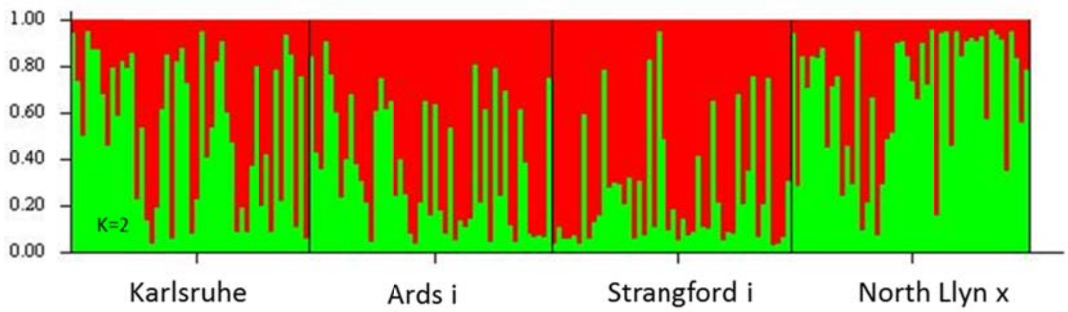


Figure 7.10: Schematic of potential connectivity of screened populations

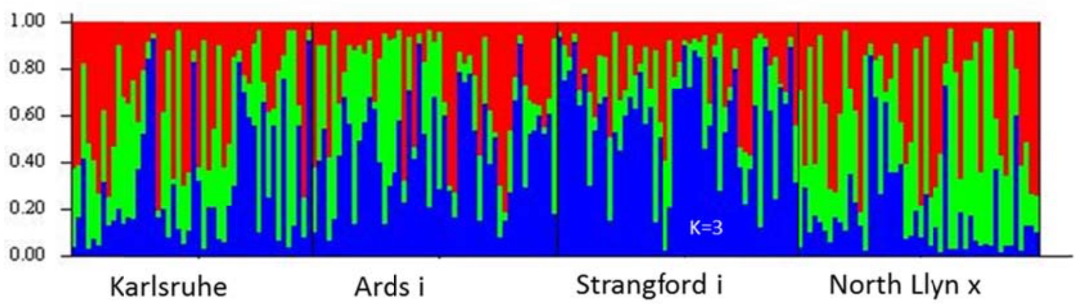
AMOVA for microsatellite loci showed a very small and negative (-0.75%) genetic variation among the four populations. Negative values do occur within AMOVA and generally coincide with non-significant P values. The remaining genetic variance was explained by differences among individuals within populations (46.7%) and within individuals (54.1%). The global Fst value was very low (-0.007) and non-significant ($p > 0.05$), therefore indicating little variation between populations overall. The close values suggest a lack of clustering within or between the populations.

During STRUCTURE analysis (Figure 7.11), it was intended to select the most probable number of clusters (Δk) while considering all populations from analysis of results in STRUCTURE Harvester based on the selection criteria outlined by Coscia *et al.* (2013). That is, the highest number for L(K) (Figure 7.12) and the highest Δk value (Figure 7.13). Results therefore initially suggested that k=4 or k=5, however, from examination of the STRUCTURE bar plots, it was concluded that it is likely that k = 1 or k = 2. It is thought that as the L(k) graph (Figure 7.12), continues to increase and does not plateau or decrease, that this signifies that there is no inferred clustering or significant genetic structuring between the populations.

(a)



(b)



(c)

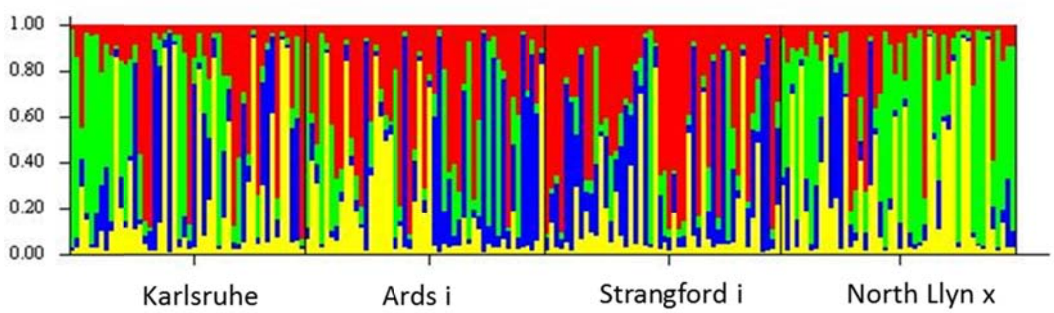


Figure 7.11: STRUCTURE bar plots (a) K = 2; (b) K = 3; (c) K = 4

It was concluded that the Bayesian STRUCTURE clustering approach using multilocus microsatellite genotypes failed to detect population structure. In addition, the symmetric proportion of individuals assigned to putative clusters indicated little or no genetic structure.

It is considered that the potential lack of clustering is also supported by the lack of variation recorded within the AMOVA analysis.

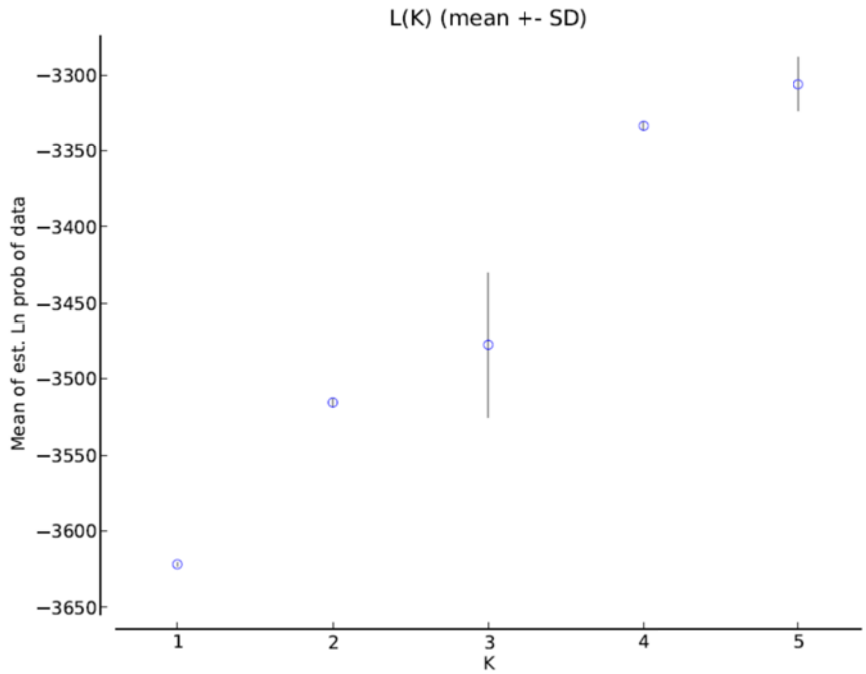


Figure 7.12: STRUCTURE Harvester L(K) graph

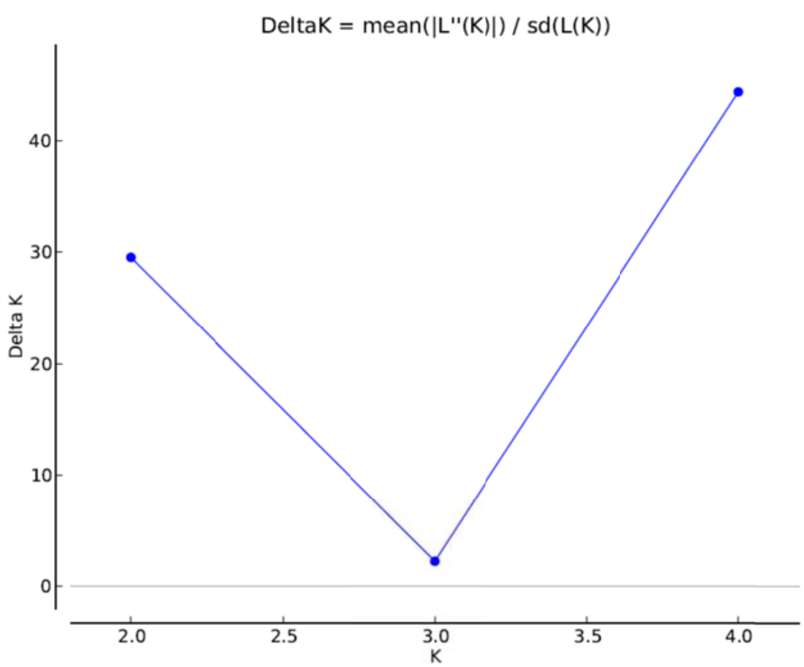


Figure 7.13: STRUCTURE Harvester DeltaK graph

7.5 Larval Dispersal

Modelled dispersal of *Modiolus modiolus* larvae from the Irish Sea populations (Ards, Strangford, North Llyn; Table 7.7) within this study was carried out by Bangor University using the methodology as outlined in Coscia *et al.* (2013). The modelling involved the development of a 3D hydrodynamic model to reproduce observed barotropic and baroclinic circulation, and residual currents, associated with the Celtic Sea front. Secondly Lagrangian particle tracking models (PTMs) were used to predict larval dispersal. As dispersal of *M. modiolus* larvae is poorly understood, the pelagic larval duration (PLD) is also not well defined. Schweinitz and Lutz (1976) suggested that larvae remained in the water column for 30 days, therefore this was chosen as the PLD within the model.

The model was tested against one migration strategy; passive vertical larval migration, that is, no vertical migration. For the scenario, cohorts of 10,000 larvae were released at the sample locations and were released 6 times with start dates chosen each month (April to September) and the PTM simulation tracked for 30 days.

Full model illustration results are presented in Appendix G. Examples of the results are presented in Figures 7.14 to 7.16. The simulation results show that there is a general southerly movement of particles from Irish release sites, and a slightly greater chance for more northerly movement after 30 days for Welsh release sites.

Work carried out by Marine Scotland (Gallego *et al.*, 2013) focussed on the potential connectivity of Marine Protected Areas in Scotland provides a simulation of spawning release from selected MPAs, and the distribution and settlement of *M. modiolus* larvae from three selected Marine Protected Areas (MPAs). The aim of that study was to predict the probable extent of PMF species transport from available data (Gallego *et al.*, 2013).

Within the model, larvae particles were released over each *M. modiolus* peak spawning period (spring and early summer) with a larval settlement window of 30-40 days. The model released particles from 3 MPAs (Noss Head, Fetler to Haroldswick and Small Isles, MPAs with known presence of *M. modiolus* beds). The study intended to identify whether larval particles may settle in other MPAs. The results showed that the potential distribution of offspring is relatively wide but connectivity potential of the MPAs is not very strong, resulting from a relatively long PLD period but limited distribution at origin within the proposed MPAs (Gallego *et al.*, 2013); Figure 7.17.

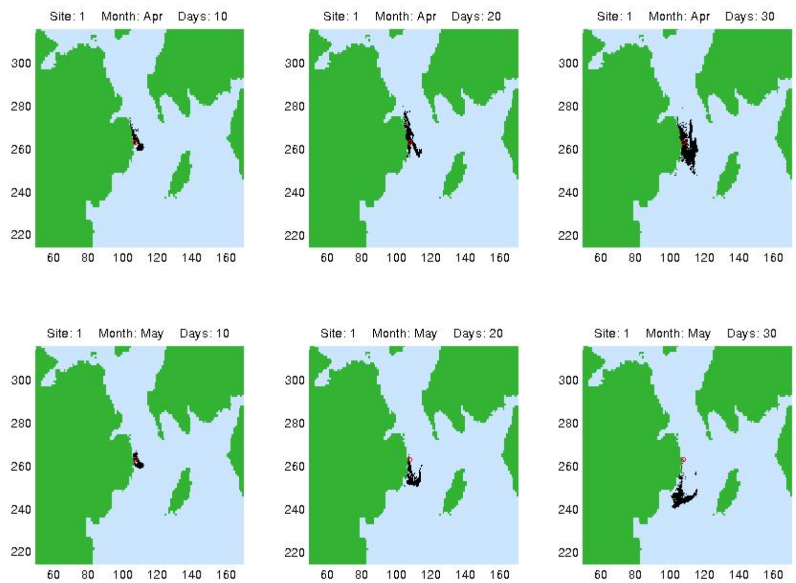


Figure 7.14: Ards Peninsula Site i - larval dispersal, April after 10, 20 and 30 days

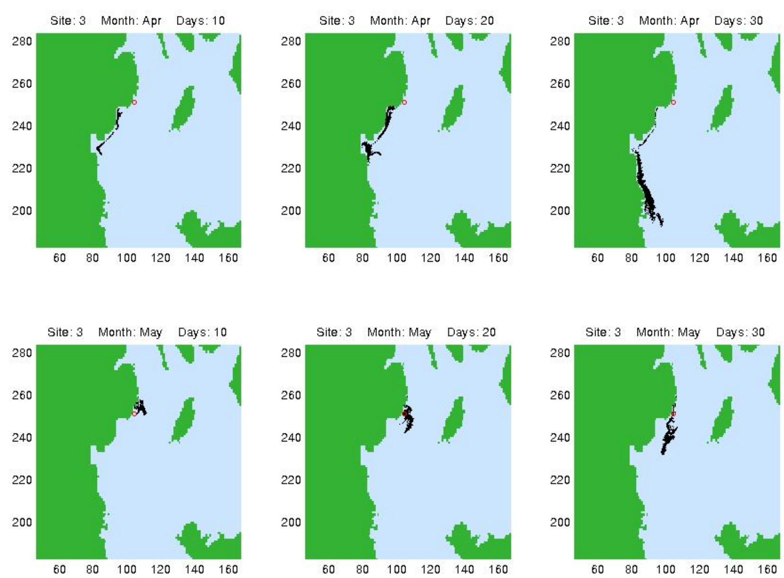


Figure 7.15: Strangford Lough - larval dispersal, April after 10, 20 and 30 days

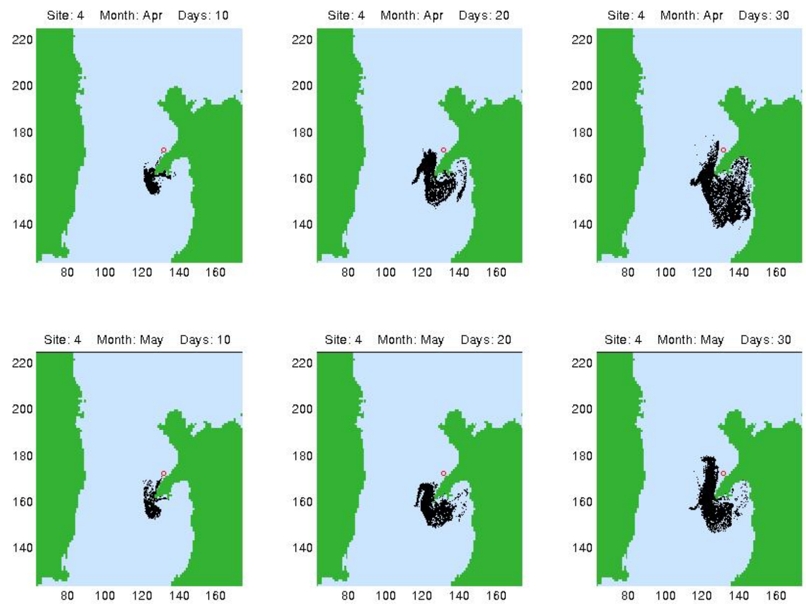


Figure 7.16: North Llyn Site i - larval dispersal, April after 10, 20 and 30 days

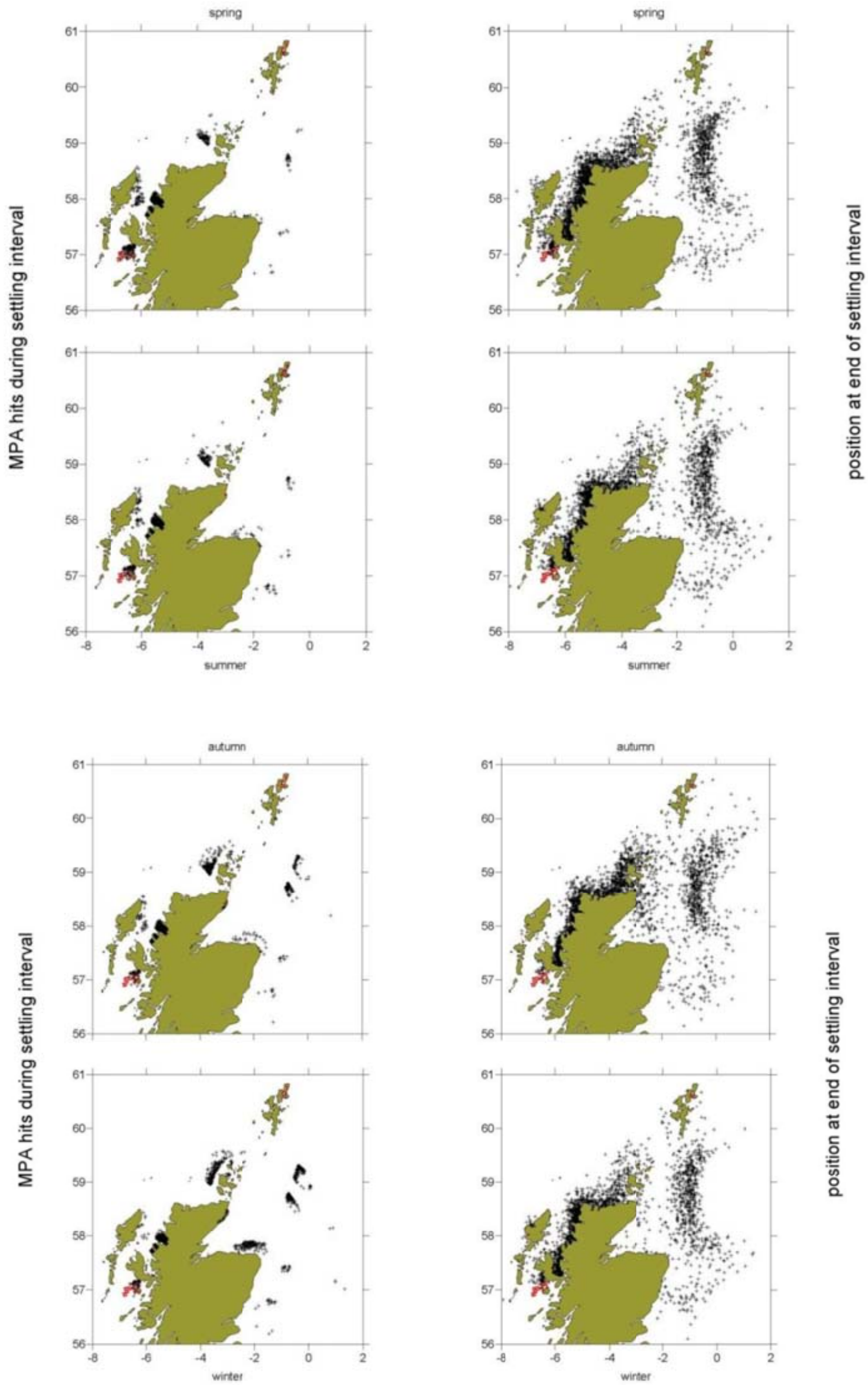


Figure 7.17: Distribution of *Modiolus modiolus* particles from Scottish MPAs (left = start position; right = end position

Source: (Gallego *et al.*, 2013)

7.6 Discussion

It has been acknowledged that genetic diversity and population connectivity has in the past, not been incorporated into the design and placement of Marine Protected Areas (MPAs) (Bell, 2008). In this study, we tested the use of genetic markers to assess the level of connectivity between populations of the Priority Marine Habitat (PMH) *Modiolus modiolus* beds.

7.6.1 Genetic differentiation and Primer development

A phylogenetic rexamination (Cytochrome Oxidase 1 subunit; CO1) of *M. modiolus* bed samples with inclusion of additional survey locations from around the UK confirmed the results presented by Halanych *et al.* (2013), that 2 distinct mitochondrial lineages exist.

The mitochondrial COI gene is one of the most popular markers for population genetic and phylogeographic studies across the animal kingdom (Derycke *et al.*, 2010). Although, in general, good results were obtained from the Halanych *et al.* (2013) study and the supplementary results obtained in this study, the resolution of the COI gene is concluded as not being suitable for the examination of population structure within a more restricted geographical area and more specific markers were therefore required.

Interestingly however, a small scale initial study was carried out in parallel to determine the suitability of the COI gene to determine speciation of mussel spat (spat that are too small to identify by eye around 2mm to 10mm in size) and whether the marker would be distinguishable when processed against the whole animal (rather than just the adductor muscle). Work is still in progress and no statistical analysis has been undertaken so far – however, informal results showed that the spat tested were *Modiolus modiolus.* Further work on this will be carried out by Robert Cook, Heriot Watt University, to determine whether spat settlement at *M. modiolus* restoration sites are in fact *M. modiolus* or are another mussel species.

Microsatellites have been isolated and characterised for a number of marine bivalve species and have been shown to have a relatively high efficiency for population analysis (Wang *et al.*, 2013). However, no study has previously developed or used microsatellite markers to assess the genetic diversity and differentiation of *Modiolus modiolus* populations.

Diz and Presa (2009) discuss the merits of using expected heterozygosity (H_e) versus allelic richness (A_r) as an estimate for sample diversity in mussel populations. They concluded that allelic richness is more appropriate for the estimation of sample diversity than H_e and therefore gives a better estimation of genetic diversity in candidate populations for enhancement, conservation and selection programmes (Diz and Presa, 2009). Their results showed that allelic richness for the mussel *Mytilus galloprovincialis* was significantly higher within the sampled estuaries (Rías) than compared to populations sampled from the Atlantic Iberian. As there are no comparative studies presenting allelic richness for *Modiolus modiolus*, it was not possible to make a judgement based on these results. However, some assumptions can be made, for example: highest allelic richness was observed within the Strangford population (mean = 21) compared to the lowest value reported within the North Llyn population (mean = 13) suggesting that perhaps the large number is related to large effective size of the local populations, and suggests that these populations may require further attention with regard to putative correlation of allelic richness of neutral markers; and there is the potential that inbreeders exhibit much more variation in allelic richness among populations than do outbreeders (Schoen and Brown, 1993).

Overall, low genetic differentiation (and therefore more gene flow (Bell, 2008)) was recorded between the Ards/Strangford and Ards/Karlsruhe populations (Figure 7.10); and all loci reported high levels of polymorphism, suggesting that these are panmictic populations.

The expected heterozygosity was higher than the observed heterozygosity for all loci in all 4 populations and the inbreeding co-efficient F_{is} was significant and positive for all populations; suggested likely results of the Wahlund effect. That is, due to the co-existence of genetically distinct cohorts within sampling location (Coscia *et al.*, 2013).

A further explanation may be the population sampling data. Sampling within the populations may reflect single recruitment cohorts. For example, (taking only the length of the mussel into account; see Section 7.4.2) the variation of the individual mussel size might give an indication into that population's recruitment events. Figure 7.18 below shows the percentage of mussels classed as small (<50mm in length), medium (<100mm, but >50mm) and large (>100mm) within each of the sampled and screened populations. The results may suggest that populations with varying sizes of the individuals (such as Ards 1 and 2, Karlsruhe and Strangford 1 and 2 and Oban for example) may have regular (and recent in the case of small individuals) recruitment events, whereas, the North Llyn populations (and Ards 2012) may not. This analysis potentially supports the microsatellite results obtained within this study, and suggests that if the North Llyn populations recruit less regularly or are self-recruiting, as also suggested by the larval dispersal models then overall connectivity may be reduced. In addition, anecdotal diver evidence from sampling events indicated that the Ards populations in particular contained varying sizes of individuals when compared to the North Llyn population. However, the size data may be classed as biased as not all sites were sampled in the same, non-biased way. Further work would be required in order to ascertain size and recruitment cohorts of each population (R. Cook, Pers Comms.).

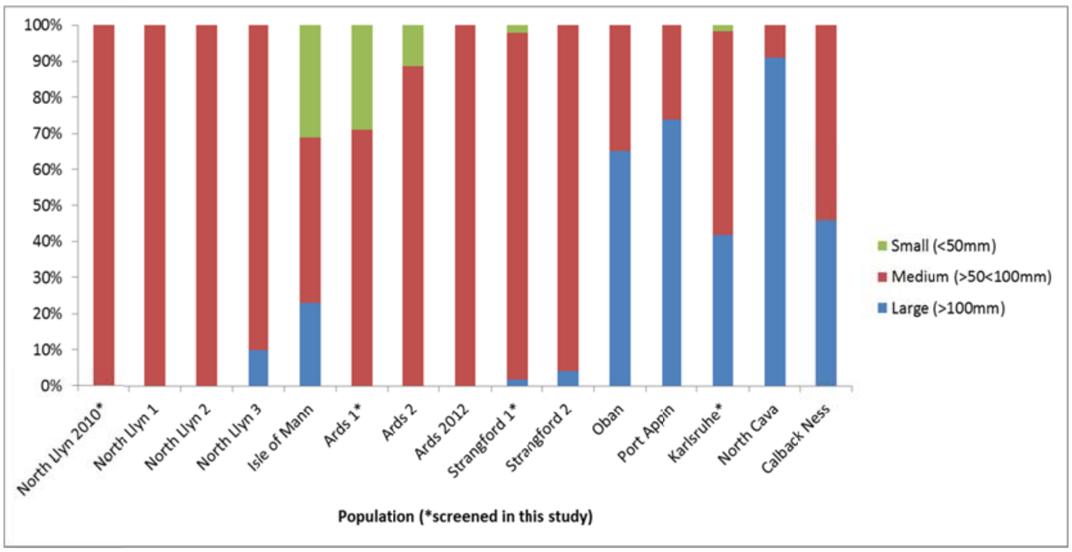


Figure 7.18: Percentage of small, medium and large individual mussels within sampled populations

The highest number of alleles was reported within the Strangford population, perhaps suggesting the richest genetic diversity of the 4 populations. However, a high degree of deviation for the HWE within this population, as well as the other 3 was noted, suggesting heterozygote deficiency.

Heterozygosity is an important measurement for population diversity (Wang et al., 2013) and a significant deficiency is a phenomenon already observed in a number of marine bivalves, but the reason for which remains relatively unknown (Diz and Presa, 2009); although inbreeding, null alleles and selection may contribute. Microsatellites in molluscs are known to be particularly susceptible due to technical artefacts, e.g.

amplification failure during PCR, incorrect genotyping or sampling drift due to small sample sizes (Diz and Presa, 2009).

Within this study, null alleles were present within all populations for all loci. Average null allele frequencies ranged from 17% (Karlsruhe and Strangford) to 24% (North Llyn). However, genetic differentiation as measured by F_{st} values calculated before and after ENA correction for null alleles showed little difference, therefore suggesting that the null alleles were not influencing the F_{st} estimates.

Low, but significant differentiation was observed between the North Llyn and the Northern Irish (Ards and Strangford) populations, and a weak (but non-significant after Bonferroni) differentiation was observed between North Llyn and Karlsruhe, possibly suggesting that the North Llyn population is the most isolated. The overall weak differentiation and panmictic nature between Ards, Strangford and Karlsruhe could suggest that no apparent restriction in gene flow occurs between these 3 populations screened during this study suggesting that these *Modiolus modiolus* bed populations are genetically connected. The continuation of marker development and the screening of more populations (in particular Isle of Man and west Scotland) may strengthen the statistical results presented within this study, and may represent connecting populations.

7.6.2 Management Implications

Habitat connectivity (including genetics) of marine organisms has been cited as a major concern to the maintenance of marine biodiversity as discussed in Chapter 5 of this thesis. Von der Heyden *et al.* (2014) suggests that despite the large number of published articles that state the necessity of using genetic data for management and conservation, very few use data applicable to real-life situations (von der Heyden *et al.*, 2014) or do not actually apply the genetic data generated to a management perspective; a sentiment that is agreed with in this thesis.

Understanding of the connectivity of habitats and species contributes to making informed decisions in a number of key marine conservation and management areas. For example, the design and selection of Marine Protected Areas (MPAs), the placement of offshore developments (such as wind farms and tidal/wave devices), a measure of biodiversity, conservation/biodiversity restoration programmes and the selection of appropriate management options (including fisheries management, invasive monitoring, maintaining connectivity corridors etc.) to name a few.

Fisheries

Particular focus on the connectivity of MPAs tends to be directed at the benefits of commercial fishing stocks. That is, no-take fishing reserves may increase fisheries stocks for neighbouring fishing grounds, but knowledge is needed to ensure connectivity of these MPAs, to guarantee maintenance of gene flow between fish stocks e.g. between juvenile and adult habitats etc. (Botsford *et al.*, 2009; Hedgecock *et al.*, 2007; Gillanders *et al.*, 2003). However, little thought is given to the connectivity of the habitats that these fish may call home, whilst in the MPAs. Many studies have been conducted on the survivorship and importance of benthic habitats to commercially valuable fish species (Thrush *et al.*, 1998; Kaiser *et al.*, 2000); In many cases it is reported that juvenile fish have a greater chance of survival in structurally complex habitats (although results vary between habitats and species) (Bradshaw *et al.*, 2003).

Therefore it is proposed herein that the connectivity of priority benthic habitats is of upmost importance to the viability of many commercial fisheries and the overall biodiversity of an area. This will ultimately contribute to a number of the Good Environmental Status (GES) descriptors under the MSFD. A summary of the association with benthic habitats and the 5 of the 11 descriptors is shown in Table 7.10. Removal or damage of the habitat can have a knock on effect to other areas of the marine ecosystem as a whole, and will result in a failure to achieve GES.

Table 7.10: Association of Benthic Habitat with the MSFD Descriptors

MSFD Descriptor	**Importance of priority benthic habitat (including *M.modiolus* beds)**
Biological diversity	*M. modiolus* beds for example support a wide range of benthic epi- and infauna. Loss of the habitat would ultimately lose the other associated fauna.
Populations of commercially exploited fish and shellfish are within safe biological limits	Providing refugia, nursery and feeding areas - protection within MPAs would allow for the provision of no-take areas or other fisheries management
Marine food webs	Benthic habitat provides a food source to other organisms, through supporting prey organisms e.g. invertebrates that live in the habitats are food for fish etc.
Sea-floor integrity.	Benthic habitats in particular *M. modiolus* beds stabilise the seabed through the development of their habitat. Loss of a bed may make the seabed in the area more prone to hydrodynamic forces.
Permanent alteration of hydrographical conditions	Removal of damage to a benthic habitat can alter the hydrodynamics depending on the size, extent and location of the structure.

Restoration

It is well understood that *M. modiolus* beds (and other benthic habitats) are particularly susceptible to damage from certain types of fishing gear (Roberts, 1975; Rees, 2009b; Rees, 2009a; Rees *et al.*, 2008), and the destruction of the *M. modiolus* beds in Strangford Lough, Northern Ireland by scallop dredging over the last few decades is well studied and documented (Roberts *et al.*, 2011) (see Appendix C). The case study example of the Strangford Lough is an example of how, despite best intentions and effort to protect a habitat, the overall management strategy of designation at SAC level under the Habitats Directive, has systematically failed; resulting in destruction of the habitat.

Following persistent lobbying by the Ulster Wildlife Trust to the UK Government, a complaint was submitted to the European Commission in 2003 citing lack of protection of the reefs. As a result, the Department of the Environment and the Department for Agriculture and Rural Development in Northern Ireland were faced with the decision – resolve the situation, or face infraction fines (see www.ulsterwildlife.org).

A plan was outlined to resolve the situation and includes the commitment to a 'Total Protection Zone' which will include the restriction of any potentially damaging activity such as fishing, diving, anchoring and mooring within a defined area, and permits and tracking systems for pot fishing (Ulster Wildlife Trust, 2012; Roberts *et al.*, 2011).

As an additional measure, the concept of physically restoring the reefs has also been proposed. This would involve the translocation of *M. modiolus* specimen from healthy beds outside the Lough into the Lough (Roberts *et al.*, 2011) and concept that has been implemented previously, particularly with regard to coral reefs e.g. the Greater Barrier Reef, to maintain and restore disturbed areas.

The issue of success with a proposed restoration project ultimately leads to a number of questions, the main one being: What do we need to know to ensure restoration is successful?

The Great Barrier Reef Marine Park Authority position statement recognises that translocation/re-introduction (including biodiversity reconstruction) of marine species can involve serious impacts to the receiving ecosystem, human health and industry. It is acknowledged that the interactions between species and the marine environment are complex and that the ecological implications of species transplanted between locations are not fully known. Therefore, in order to manage and mitigate the impacts from these activities a well-structured risk-based approach is necessary (Australian Government, 2007).

The primary risk associated with a biodiversity reconstruction programme is the general susceptibility of the donor specimens to potential stressors in the new/receiving environment including, but not limited to: contaminants/pollution, disease, parasites, temperature variability, exposure, predators and anthropogenic impacts. It is well documented that stress is considered a major factor in the outbreaks of viral disease in marine invertebrates (Morley, 2010). Having a full understanding of the ecosystem in general (both donor and receiving) will ultimately increase the chances of restoration programme success.

It is known that genetics play a key role on specific resistance to disease (Sheridan *et al.*, 2013) as the genetic make-up of the host dramatically affects disease or stress (including parasite) susceptibility. It is therefore suggested that, from results obtained in this study, that the Ards, Strangford and Karlsruhe populations lack differentiation, then their genetic susceptibility to stressors, may therefore be the same.

It is suggested that the Outer Ards Peninsula populations may be selected as the donor population for transplant into Strangford Lough and other aspects need to be taken into consideration. It is essential that the donor site is deemed to be "healthy", both from a genetic point of view, but also with regard to the stability of the bed. Knowledge of the extent, structure and age of the donor may be useful in making a final judgement. It would be counter intuitive to replace the beds in Strangford through the destruction of the Ards beds. How much can be removed to still leave a viable stable bed? In the same vein, methods for excavation of the donor specimens also need careful planning. Research would therefore be required on the best options for removal, e.g. manual vs. industrial methods. In addition, understanding what methods of transplant would be most efficient is a requirement. Will it be the case that samples will be just placed on the seabed, or is there merit in partial burial? And what are the factors employed to account for the possibility of handling stress?

Translocation of parasites and shell epifauna is also an important consideration. Parasites and epifauna may be the same in both ecosystems, but the conditions at the new site, may be more favourable to the increase in parasites, therefore increasing stress on the host.

Parasitic screening of the *M. modiolus* samples used within this study was carried out by University College Cork. Initial results suggested that there were no unusual parasites present, and no particularly high loading was observed between the sites (Dr. S. Culloty; Pers. Comms); this work is currently still in progress. This would therefore suggest that there is no reason for not going ahead with the Ards to Strangford transplant, with regards to concerns about parasites.

Larval Dispersal, Barriers and Stepping Stones

Results from larval dispersal models confirm that there is the possibility that larval dispersal has the potential to be wide reaching. However, whether the dispersal will maintain connectivity of MPAs is unknown. Larval settlement location is dependent on oceanographic processes and larval duration. Therefore, further work is required to provide more accurate larval duration data. It will be particularly important to screen populations in the Isle of Mann in order to determine whether they act as stepping stone habitats between the Welsh and Northern Irish populations.

It is possible that due to the potential connectivity of the *M. modiolus* beds in this study, that stepping stone habitats provide an important role in the gene flow of this species. Known bed distribution (as shown in Figure 7.8 for this study; and Figure 4.4, for other beds) is principally located to the west of the UK and perhaps provides a source of "stepping stones" for genetic material between the main bed sites. Smaller areas of *M. modiolus* currently not classed as beds may also be present in between, and may have the potential to become beds in the future, if recruitment is maintained. Knowledge of potential suitable habitats therefore would be advantageous (as discussed in more detail in Chapter 8).

Although further work is required to develop more markers and screen more *M. modiolus* populations, initial results from this study suggest that some of the *M. modiolus* beds around the UK are, in principle, connected. An implication that arises from completely connected habitats is the potential for the development of barriers to the gene flow and potential for genetic shift, this may, for example be in the form of a tidal array or wind farm development.

With regard to barriers, potential impacts include the alteration of local hydrodynamics which in turn may result in disruption to the movement of dispersed larvae (and therefore genetic material). If for example a bed was genetically distinct, the placement of a barrier, in theory would not cause much of an impact, as recruitment would not occur out with the population. However, in this case, *M. modiolus* beds in the UK are likely to rely on recruitment from a number of population sources (although no source/sink models have been tested at this stage due to lack of data). If a barrier is inadvertently created, there is the possibility that, if a population becomes isolated, that population may cease to be viable and may eventually be lost.

Careful consideration is therefore required from a marine planning perspective to ensure that connectivity between sites is maintained, whilst also retaining marine development opportunities.

7.7 Conclusions

A contemporary focus of marine conservation management planning is moving towards an understanding of the connectivity of marine ecosystems and directed at the design of Marine Protected Areas. Cowen and Sponaugle (2009) provide a comprehensive review of marine connectivity studies and conclude that theoretical studies and modelling need to be complemented by hard science in order to lead to better MPA design; and that global climate change has the very real potential to disrupt connectivity (as discussed in Chapter 8).

Further development is required on the type of connectivity screening undertaken on priority marine organisms to better inform policy and marine spatial planning. It would be beneficial to screen potentially isolated populations or geographically distinct populations (e.g. sampled from east Scotland and Norway) to confirm applicability for microsatellite use within these populations. Within this study, microsatellites were identified as the genetic tool of choice based on the available resources at the time of study. However, it is acknowledged that a number of other markers can also be used (e.g. SNPs; Single-Nucleotide Polymorphisms, RAPID, and Amplified Fragment Length Polymorphisms; AFLP).

Issues arise with regard to the use of different techniques from a marine management perspective, therefore resulting in potential deviations in resolution. In order to provide the best tools for decisions makers, continuity of methods would be recommended.

Although there is the possibility to carry on optimising the markers outlined in this study, the general move towards more genotypic type screening may have its merits. Although, this is not to detract from what has been achieved within this study - as no previous screening of *M. modiolus* populations has been carried out. It would be interesting to screen the distinct Pacific population clade as identified by Halanych *et al.* (2013) with the markers developed here in order to determine their sensitivity. It would be hypothesised that they would show complete differentiation.

There is the possibility that given the longevity of *M. modiolus* and their ability to spawn numerous times in a lifetime there is the considerable potential for genetic mixing (as discussed by White *et al.* (2009) with regard to orange roughy; *Hoplostethus atlanticus*). Genetic screening of the whole genome would allow for site specific markers to be adapted, and the possibility therefore to detect site specific adaptations and genetic structure.

Overall, it is concluded that given the potential connectivity of this habitat (on the west coast of the UK at least) then future management and planning should take this into account, and *M. modiolus* beds in the UK, particularly the Northern Irish (and North Llyn populations) could be managed together, as one conservation unit, rather than as separate beds.

7.8 Chapter 7 Summary

- Results show that *Modiolus modiolus* beds between the Atlantic and Pacific are phylogenetically distinct based on COI mitochondrial phylogeny.
- Overall, no evidence for population substructure was identified within the Atlantic clade
- Microsatellite markers were developed and used to screen populations to determine connectivity within the Atlantic clade
- Microsatelite marker analysis reveals that The Ards, Strangford and Karlsruhe populations in the UK are genetically similar
- The North Llyn population is significantly different from the Ards and Strangford populations, and weakly different from Karlsruhe
- Larval Particle Tracking model results within the Irish Sea indicated that there is the possibility of the Ards and Strangford populations mixing; and that it is unlikely that the North Llyn populations mix with those in Northern Ireland. This may suggest self-recruitment at North Llyn and also supports the results obtained from the microsatellite screening.
- Within the populations screened, no distinct population sub-structure or clusters was identified – results which are comparable between both sets of markers tested (COI and microsatellites)

Chapter 8. Discussion and Conclusions

It was acknowledged that in order to implement MSP and to achieve GES under the MSFD (Borja *et al.*, 2011), an understanding and knowledge of all ecosystems including priority species/habitats, and their functioning is necessary. As it was not possible for the research to cover "all ecosystems" within one project; it was decided to focus on one case study species/habitat, but to develop and test methods that are applicable to a wide range of species and habitats, in different geographic settings.

In this thesis a number of discrete studies have been conducted to investigate the Priority Marine Habitat, *Modiolus modiolus* beds and the implications of climate change and protected area management on them. In the thesis a number of existing and new methods for the prediction of habitat distribution, management and connectivity have been applied. As set out by the aims and objectives these have been used to demonstrate the potential value of these "tools" to marine conservation management.

This thesis gained inspiration from a number of areas. Notably, from both a personal experience point of view and from a review of the contemporary marine policy and legislation, it was evident that there was a gap in the science and policy interaction; and how to make science more usable to policy. A number of published studies and key areas were consequently identified as providing further inspiration to the design of the studies. In summary, Ross and Howell (2013) and Jones *et al.* (2012) outlined the use of species distribution modelling within a marine management context. These studies were developed upon and led to the investigation of how these methods could be integrated with potential climate change scenarios (Chapters 4 and 5). Studies on how MPA management effort could be measured were also investigated. A review of literature in this area was limited, and no study was identified where a prediction of management effort was made. This idea was further developed in order to create the of prediction tool outlined in Chapter 6. The use of molecular markers to study connectivity of *M. modiolus* was also limited. The methods outlined by Halanych *et al.* (2013) were retested with additional populations in order to determine community sub-structure within the subsequently identified Atlantic *Modiolus* clade. However, more specific markers were required. The use of microsatellite marker methods, as used by Coscia *et al.* (2013) provided the outline methods for development, population screening and analysis of *M. modiolus* specific markers.

The use of Species Distribution Models (SDMs) is widespread, but few focus on modelling the distribution of habitat forming species (in their habitat form), and seemingly, none introduce the potential for integrating connectivity studies within them, either through modelling or as a parallel/complementary "ground-truthing" exercise.

The studies herein tested different SDM methods for PMHs against an increased ocean temperature scenario (Chapters 3, 4 and 5) and also explored the implications that a changing climate may have on their distribution within currently designated MPAs. In addition, a tool was developed to predict the effort required to manage these MPAs (Chapter 6); and new knowledge on the ecology of *Modiolus modiolus* through the first study on the site specific genetic connectivity of *M. modiolus* beds in the UK was developed (Chapter 7).

In this discussion chapter an overview is provided showing the interconnection of the individual studies conducted. Key outcomes are identified and suggestions made for future research avenues.

8.1.1 Project Summary and Implications of Research

As part of the aims and objective of this thesis, the development and use of conservation management tools that could provide a straight forward, cost effective and applicable method for management assessment was an important goal. This was a particular gap that was identified through the review of policies, and associated literature. There was no clear definition for how management decisions would be based, and it had been acknowledged that it may be unlikely that new scientific data would be generated for all the MSFD descriptors (mainly from a financial and resource perspective; an understanding from discussions with stakeholders at MPA workshops and consultations).

The implementation of the MSFD is directing European marine research towards the co-ordinated and integrated assessment of sea environmental status, following the ecosystem-based approach (Borja *et al.*, 2011). In order to determine GES effectively there needs to be consensus among member states as to the set of biological effects that will be used within MSFD monitoring programmes (Lyon *et al.*, 2010).

Indicators for the Biodiversity descriptor (a particular driver for this thesis) established by the European Commission (2010) provide an overview of what should be monitored to provide evidence for establishing whether an area or species has GES. These indicators loosely set areas that help answer the question set above (what do planners need to know….?) and include: i) species/habitat distribution; ii) distributional pattern; iii) population abundance; iv) population demographic characteristics; v) habitat area, and volume; vi) condition of habitat and species; vii) physical, hydrological and chemical conditions; and viii) composition and relative proportions of ecosystem components (habitats, species). In this thesis, evidence is generated that could be used by marine managers to contribute to the understanding of GES and on-going monitoring under the MSFD of *M. modiolus* beds in particular, where data are lacking.

The species distribution models in particular were assessed from a usability point of view (Chapter 3) and the critique showcased the variety of model interfaces currently available to policy makers. However, issues arise with the effort required to learn how to use the interface, particular quirks within the software (e.g. data formatting) and the gathering of suitable environmental parameters with which to run the models.

In the thesis an outline of available data sources is provided and through the results of the studies in Chapters 4 and 5 has provided modelled outputs for 10 OSPAR PMHs throughout the North East Atlantic that could be considered within a policy setting now. Publication of the studies disseminates the methods to a wider scientific and policy audience so that the methods and data can be considered, a sentiment that was a strong driver for this thesis overall.

In summary, results from this thesis showed that there is the potential for *M. modiolus* beds to be "lost" from UK waters by 2100 (Chapter 4); although, movement northwards is a possibility – as is the expansion, contraction or movement of other PMHs (Chapter

5) throughout Europe. However, limitations in the use of SDM on habitat forming species (as opposed to motile species e.g. fish) is acknowledged when referring to "loss". The limitations identified are discussed in this chapter (i.e. the habitat is unlikely to be completely lost, but may be hindered; or may adapt) and makes suggestions for further work to improve knowledge in this area. The study in Chapter 6 showed that the MPAs that protect PMHs vary in their requirement for management, and a prediction indicator was developed. Results from this study suggested that MPA management resources could be accounted for prior to formal designation, potentially enabling selection of appropriate management measures to appease public opinion; or to account for cumulative impacts, as discussed in this chapter. This is an area of research priority as outlined by the Scottish Government (Gallego *et al.*, 2013) and modelling (e.g. larval dispersal) only provides part of the story. The final study in this thesis, although perhaps not fitting the set criteria of cost-effectiveness, provided essential new data on the connectivity of the *M. modiolus* beds. The results showed that some of the beds around the UK appear to be connected, therefore need to be managed in such a way as to maintain this connection; and that also allows for management decisions to be based, for example the choice of restoration strategy. In addition, further work would be required to confirm whether the population at North Llyn is in fact isolated, or whether there are stepping stone populations that support it.

Ecosystem Based Management

The concept of an "ecosystem-based approach" (Ecosystem Based Management; EBM) was adopted at the Earth Summit in Rio, 1992 becoming an underpinning theory of the Convention on Biological Diversity, and was later described as (http://jncc.defra.gov.uk/page-2518):

"a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way."

This concept suggests that both conservation and sustainable use/development are equally important, i.e. neither one should be given priority over the other. However, in reality this is rarely the case, for example, as stated in the Shetland Regional Marine Plan (NAFC Marine Centre, 2012), that is, developments would be given precedent over areas of conservation interest, if there is an overwhelming economic benefit.

A central concept in this thesis is that "knowledge is power", and that knowledge of an ecosystem would ultimately lead to better decisions (involving said ecosystem) to be made. Therefore an "ecosystem-based approach" can only truly be implemented when we have the appropriate knowledge on, for example: i) where an ecosystem occurs (now and in the future), ii) how much or what type of cumulative impact it can endure, or iii) how sensitive it is etc. This ultimately would enable managers to better implement sustainable management – only placing developments in suitable areas, based on the ecosystem – not just economic benefit.

8.2 Modelling, Connectivity and Management

8.2.1 Stepping Stones

Marshall (2011) stated that a crucial stage has been reached in the application of marine species distribution models and that consideration is now needed on the endpoint application of these models. That is, actually applying modelling outputs to management and planning. Findings of this thesis are in agreement with the statement, furthermore it is clear that management and modelling needs to be combined with science to make the outputs meaningful. It is acknowledged however within this thesis, that this inevitably costs money and is therefore not always possible. It is demonstrated herein that useable data can be developed with limited financial resource.

The combination of genetic and distribution model analysis used within this thesis provides an insight into the evolution and ecology of *M. modiolus* beds, and contributes new knowledge that could be incorporated into marine spatial plans and MPA management measures.

Considering the SDMs from a baseline perspective (present day; 2009) the results showed that potential most suitable habitat for *M. modiolus* beds existed across a relatively narrow geographic range within UK waters, with the majority of habitat located close to the coast (possibility in sea lochs etc.) along the west of the UK, with other patches seemingly less continuous in other areas (e.g. to the east). When that knowledge is combined with results obtained from the genetic connectivity study, it is possible that "modelled" suitable habitat may play a key role in potentially providing stepping stone habitat for the established beds in reality.

By stepping stone habitat, it is meant, that suitable habitats between established beds may provide suitable settlement and growing habitats for *M. modiolus.* Although these areas are unlikely to be classed as beds initially, they are beneficial in 2 ways. Firstly, if development of the settled larvae is successful and spawning ensues then these larvae carry on the dispersal route, potentially ending up within an established bed, and therefore increasing the bed's recruitment. Secondly, these suitable habitat areas, if not disturbed, may eventually develop into beds in their own right, and therefore contributing to the biodiversity of the area.

There is also the consideration of individual *M. modiolus* specimen. Given the extent of their present and historical distribution (as shown in Chapter 3) there is the possibility that these specimen (although not defined as “beds”) may also be contributing to the recruitment through larval dispersal,

Therefore having an understanding of essential stepping stone habitats is crucial to the management of the beds themselves. The study has shown that there is a high possibility that the *M. modiolus* beds around the UK are genetically connected (taking into account sites near the north of their UK distribution; Orkney, and to the south; Wales and Northern Ireland). This would therefore suggest that stepping stone habitats must play a role. Larval dispersal models and known larval duration would indicate that the physical movement of *M. modiolus* directly between the screened sites would be impossible. Although other beds have been sampled, they are yet to be screened; they too, seem too far apart to account for direct transport on their own although they will of course contribute.

Management considerations are therefore needed to account for the possibility of stepping stone habitats, and SDM methods would allow for that. It is surmised that potential suitable habitat should be incorporated into planning aspects for MPAs, although treating them as priority habitats themselves is not suggested (that would be impractical, and would hinder sustainable economic development) – an appreciation of their potential importance is. To maintain genetic connectivity of an MPA, ultimately prolongs the life of the MPA and potentially leads to climate change resilience.

8.2.2 Climate Change

The second aspect of integrating the connectivity data with the modelling outputs within this thesis is to contribute to the knowledge of potential impacts to *M. modiolus* under climate change scenarios. Work carried out in Chapter 4 (see Figure 4.7; Section 4.3.2) indicated that there is the potential for *M. modiolus* beds to be “lost” by 2100 if the oceans temperature increases.

The idea that a high biodiversity habitat could be lost is a particular concern, especially when we take it into consideration alongside potential restoration programmes (moving specimens from a northern site to a southern site may result in stress induced problems, and may ultimately result in failure of the programme).

It was discussed in Chapter 4 that as *M. modiolus* is a long-lived species, it is not so cut and dry in terms of stating “if the ocean temperature increases, all beds will die (whether instantly or not)” – obviously would be an exaggeration.

There is however a real possibility that due to the stress of increased ocean temperatures, *M. modiolus* may stop spawning, or at least spawning to be hindered; or shifted seasonally.

A shift in spawning seasonality may not seem like such a big problem initially, when considered alongside temporal oceanic processes, it may become an issue. Oceanic processes shift seasonally, and currents for example moving northward during the summer, may move southward in the winter, therefore potentially changing the direction of larval dispersal; resulting in the larvae being distributed to unsuitable stepping stone habitat or source material (as discussed below) not making it to its sink. Hedgecock (1986) reported that differentiation of populations of marine invertebrates (their study involved the lobster *Homarus* sp. and the barnacle *Balanus glandula* Darwin, 1854) that have pelagic larvae can arise from either physical or biological barriers to larval dispersal, suggesting that connectivity could be affected as a result

If spawning is reduced or stopped, so therefore is recruitment. Obviously there is the possibility that the habitat will move northwards eventually, and would still therefore be present, but just in a different location, as discussed in Chapter 6, through for example, the development of the previously described stepping stone habitat. However, if it is known that populations of *M. modiolus* are in fact genetically connected, then more information would be needed to determine whether a population is contributing to the gene flow as a source or a sink population.

If the populations at the southerly limit are determined as source populations, (and we may assume that they are based on larval dispersal models and knowledge of oceanic processes) and they cease to be viable in terms of spawning, this will ultimately have a knock on effect on the other beds that rely on their larvae for recruitment.

Climate change also brings with it the possibility of invasive species. If populations are no longer able to recruit, opportunistic mussel species (or other species e.g. predators) more suited to warmer climates may start to compete for space, and a species shift occurs. Although this is seen as a potential problem currently, if this issue were accounted for within planning options, then it is an inevitability that can be positively received. For example, if the niche is inhabited by another reef forming species, is it really a problem if it is not *Modiolus modiolus*?

There is, however a chance, that given the projected length of time for climate change under our scenarios, *M. modiolus* may be capable of adaptation to the warming oceans within that time and in fact spawning and recruitment will not be hindered at all. Further work would be required to determine what impact increasing temperatures, and other climate change factors e.g. pH would have on *M. modiolus* function and viability.

8.2.3 Impact Assessment

Linking back to source and sink populations and their management, understanding the impact of industries on them is an important factor for consideration within the MSP process and would enable an additional predictive element to be tested within the predictive management tool outlined in Chapter 6. If a genetic scoring factor could be developed for the genetic importance of certain populations within MPAs, it may be possible to ascertain whether the genetic make-up of a population would ultimately contribute to management effort of an MPA. For example, would genetically distinct population need more management? Would source populations be more sensitive to cumulative impacts?

Combining the genetic analysis, management effort data and other ecological or biological data could lead to the creation of a decision support matrix with confidence indices. Such a matrix would enable decision makers to incorporate as much science as possible into policy and management strategies. Significant work would be required to establish such a matrix, but may include the following: i) evidence of panmixia, ii) source and sink identifiers, iii) life span, age, recruitment, iv) age at reproduction, and v) connectivity

There are many gaps in knowledge about cumulative impacts, general impact assessment methodology and limitations in the current analysis. Further research should seek to help improve understanding of interactions between various stressors and help inform management thresholds and limits for impacts from individual activities and cumulative impacts from multiple activities in a given area (Ban *et al.*, 2010).

It is true to say that as marine populations and ecosystems exhibit complex system behaviours, marine planners/managers and to some extent project developers cannot safely assume that the marine ecosystem (whether at a large or small scale) will recover when a stressor is reduced. Therefore, a preventative attitude is a far more robust management strategy than seeking a cure for degraded systems (Crowder and Norse, 2008). This leads to a requirement for a better understanding and quantification of risks (whether cumulative or not) to the environment from activities and/or developments. In addition, the concept of co-located MPAs will also become more prominent. A site set aside for an array of wave/tidal devices, in which other activities such as commercial fishing or shipping are excluded, might be analogous to a marine protected area and actually benefit certain species (Harrald and Davies, 2010); and in essence it has been recognised that many offshore energy developments could potentially act as *de facto* Marine Protected Areas (MPAs) (Sheehan *et al.*, 2010).

Additionally, impact assessment also needs to be considered with regard to connectivity of populations. Considering whether the placement of an activity will hinder the gene flow between populations will also need to be considered if connectivity is truly going to be addressed under the MSFD or within MSP. The results within this thesis showed that the North Llyn population is potentially different from the other populations screened (Ards, Strangford, Karlsruhe), leading to two potential scenarios that should be considered. One, as they are considered not to be connected (although this would require further verification through additional screening of more markers and populations), then the placement of an activity that potentially alters the hydrodynamics between the North Llyn and Ards/Strangford populations (e.g. wave or tidal array, wind farm etc.), may not pose too much of an issue, as it is possible that this population is self-recruiting and does not require external gene flow for maintenance. However, on the other hand, activities that may have a direct impact on the population, (e.g. dredge fishing, or placement of an energy device etc.) may severely threaten their survivability if recruitment is hindered, and no external recruitment is achieved, then it is possible that the population would be lost. These scenarios therefore outline the importance of considering connectivity in order to provide effective management of a PMH.

8.2.4 Further work

There are a number of potential areas that have been identified in the course of this thesis and would benefit from further work. Firstly, continued development of the microsatellite markers may potentially allow for better resolution and analysis of *M. modiolus* populations. A suite of perhaps 10 markers instead of the 4 used in this study would allow for better statistical analysis and source/sink models to be tested (models are generally uninformative with limited data). This would provide additional information regarding which populations are providing the majority of the genetic material. This could therefore be built into the planning of MPAs to ensure that source populations are adequately protected and that suitable precautionary methods of habitat restoration or mitigation for climate change can be introduced.

Additional screening of populations with developed markers would also be beneficial. In particular, it would be extremely interesting to screen either physically isolated populations or populations from the east of the UK and further afield such as America, Canada, Norway and Sweden. It would be hypothesised that these populations would not be genetically connected to the populations in the UK. If the results concluded that they were genetically linked, it is possible that these markers are therefore not selective enough and would therefore be deemed unsuitable for the basis of management decisions.

As mentioned above, additional work is also required to determine *M. modiolus* sensitivity to climate change. Suggested methods would include aquarium based studies where *M. modiolus* specimen are subjected to gradients of environmental variables (e.g. temperature and pH) and biological measurements perhaps from a proteomic or genomic perspective are recorded. Although as mentioned by Roberts *et al*. (2011), aquarium induced spawning of *M. modiolus* is difficult. Therefore it is not known whether spawning, in particular, would be a measureable variable under stress conditions during this type of study.

8.3 Conclusions and Closing Remarks

"The sea, the great unifier, is man's only hope. Now, as never before, the old phrase has a literal meaning: we are all in the same boat."

— Jacques Yves Cousteau, Oceanographer

Overall, the research in this thesis has provided information and knowledge to contribute to implementation of a truly ecosystem-based approach to management and effective PMH management. It is now known: i) where *Modiolus modiolus* beds occur; ii) where they have the potential to occur, now and in the future; iii) that there is the potential for them to be lost/ hindered or lack-viability if ocean temperatures increase; iv) that they may become more important to conservation at northern latitudes in the future; v) that European nations will have to work towards integrated marine conservation policies and protection when considering all PMHs; vi) that some MPAs may require more effort to manage than others and that it may be possible to predict which ones they will be; vii) that cumulative human impacts may not be the driving force for management effort; and viii) that some *M. modiolus* beds in the UK are potentially connected. The data and discussion points generated within this thesis will enable effective PMH management through the selection of appropriate management strategies. For example, it has been suggested in this discussion that *M. modiolus* beds in some parts of the UK could be managed as one entity (e.g. some areas within the Irish Sea), therefore potentially reducing management effort; restoration programme implementation if appropriate; or potential managed retreat of the beds.

Although this thesis has developed and demonstrated a number of techniques applicable to the conservation management of a PMH, it has been acknowledged that more work is still required in order to ensure that robust scientific data is available to help support management decisions. In addition, as we are all technically in the "same boat" when it comes to protection and sustainable exploitation of the marine environment, a concerted effort is needed to contribute to collaborative and coordinated marine spatial planning between nations, now and into the future.

Appendix A. Overview of Policy and Legislation

A number of conventions have been created to provide for international marine environmental protection; with the principle conventions for conservation and protection of the marine environment within Scottish waters being the OSPAR Convention and the Convention on Biological Diversity. The OSPAR convention (the Convention for the Protection of the Marine Environment of the North-East Atlantic) was adopted in 1992 and entered into force in 1998 with the aim of providing a comprehensive and simplified approach to addressing all sources of pollution which might affect the maritime area, as well as matters relating to the protection of the marine environment (JNCC, 2011a). The Convention on Biological Diversity (1992) was the first global treaty to provide a legal framework for biodiversity conservation and established three main goals: the conservation of biological diversity; sustainable use of its components; and the fair and equitable sharing of the benefits arising from the use of genetic resources (JNCC, 2011a).

Together these conventions require a number of actions to be undertaken by the contracting parties in order to fulfil the convention commitments and, as a result, a number of EU and UK Directives and legislations have been created to go some way to fulfil these requirements. The purpose of this policy and literature review is to provide an overview of some of the current policies and legislations that are currently in force to provide for the protection and conservation of the marine environment.

Environmental Policy can describe a course of action deliberately taken to manage anthropogenic activities; and therefore a means for providing prevention, reduction and/or mitigation of harmful effects to the environment, and ensuring that impacts to the environment do not have a resulting damaging effect to society. This definition can apply to a number of different courses of action, from high level national/regional governmental documents to the commitments laid out by companies to protect the environment and its employees.

For the basis of this study, “Environmental Policy” has been defined as any document (or course of action) laid out by the European court or the UK government which has led, or will lead to the creation of legislation; or has been created to fulfil the requirements of a piece of Environmental Legislation. Environmental Legislation is defined as legislature that has already been transcribed in UK law at the time of writing. Examples outlined in Table A.1.

Table A.1: Examples of environmental international, European and UK legislation associated with the offshore environment

Definition		**Examples associated with Marine Conservation and environmental protection**
Conventions	A Convention is an international agreement between a number of countries, dealing with a specific subject of common concern. Conventions are legally binding and 'Contracting Parties' to the convention, and the agreement enters into force at a set period after a specified number of ratifications	• The protection of wetlands of international importance (Ramsar) • The protection of species and habitats of European Importance (Bern) • The protection of migratory species (Bonn) • Convention on Biological Diversity • Climate Change • OSPAR • The regulation of wildlife trade (CITES) • The protection of sites of international cultural or natural significance (World Heritage)
European Legislation	Since the Lisbon Treaty entered into force on the 1st December 2009, European legislation is now adopted by the European Union in the form of Directives and Regulations. European Directives require Member States to implement their provisions nationally for the benefit of Europe as a whole. European Regulations are directly implemented in Member States	• **EC Habitats Directive** • EC Birds Directive • **EU Water Framework Directive** • **EU Marine Strategy** • Catches of Cetaceans • Environmental Liability
UK Legislation		• **Marine and Coastal Access Act 2009** • **Marine (Scotland) Act 2010** • Offshore Regulations

Source: adapted from (JNCC, 2011a)

A.1 Summary of Relevant Environmental Policies and Legislation

The policies and legislations that were identified as being of significant importance to this research project were reviewed and summarised in the following sections along with any pre-existing parent policy. This enabled a wider understanding of how these policies work together. The higher level "parent policy", in this case, the Integrated EU Maritime Policy, will not be examined in any further detail at this stage of the project other than that provided below.

A.1.1 Integrated EU Maritime Policy

The Integrated EU Maritime Policy (EUMP) aims to achieve sustainable development by reconciling the economic, social and environmental dimensions of the exploitation of the seas and oceans. Within the EUMP, the Thematic Strategy for the marine environment aims to:

- Further strengthen legislation on maritime safety;
- Introduce risk assessment as an instrument for drawing up policies in the field;
- Assist developing countries so that they can apply the 'Global Ballast Water Management Programme'; and
- Introduce ballast water treatment technologies.

The EUMP has also established a programme of work which includes (Europa, 2011b):

- A European Maritime Transport Space without barriers
- A European Strategy for Marine Research
- National integrated maritime policies to be developed by member states
- A European network for maritime surveillance
- A roadmap towards maritime spatial planning by member states
- A strategy to mitigate the effects of Climate change on coastal regions
- Reduction of CO_2 emissions and pollution by shipping
- Elimination of pirate fishing and destructive high seas bottom trawling
- A European network of maritime clusters
- A review of EU labour law exemptions for the shipping and fishing sectors

This overarching maritime policy is viewed as the mechanism for a more integrated approach to achieving the desired socio-ecological outcomes for Europe's coastal and marine environments (Queffelec *et al.*, 2009). However, the major challenge facing the

Maritime Policy is to achieve delivery of its targets within other sectoral European policies such as the Common Fisheries Policy, Transport Policy and Common Agricultural Policy and with other environmental Directives including the Birds and Habitats Directives, Water Framework Directive, Nitrates Directive and the Urban Waste Water Treatment Directive (Queffelec *et al.*, 2009). The environmental pillars of this policy are discussed in more detail in the following sections.

A.1.2 Marine Policy Statement

The Marine Policy Statement (MPS) is the framework for preparing Marine Plans and will contribute to the achievement of sustainable development in the UK marine area. The MPS has been prepared and adopted to fulfil the requirement of section 44 of the Marine and Coastal Access Act 2009 (HM Goverment, 2011).

The MPS will facilitate and support the formulation of Marine Plans; to ensure that marine resources are used in a sustainable way and in line with the high level marine objectives and thereby (HM Goverment, 2011):

- Promote sustainable economic development;
- Enable the UK's move towards a low-carbon economy, in order to mitigate the causes of climate change and ocean acidification and adapt to their effects;
- Ensure a sustainable marine environment which promotes healthy, functioning marine ecosystems and protects marine habitats, species and our heritage assets; and
- Contribute to the societal benefits of the marine area, including the sustainable use of marine resources to address local social and economic issues.

The process of marine planning will (HM Goverment, 2011):

- Achieve integration between different objectives;
- Recognise that the demand for use of our seas and the resulting pressures on them will continue to increase;
- Manage competing demands on the marine area, taking an ecosystem-based approach;
- Enable the co-existence of compatible activities wherever possible; and
- Integrate with terrestrial planning.

A.1.3 Marine Strategy Framework Directive (MSFD)

> *"The EU Marine Strategy Framework Directive (MSFD) applies an ecosystem approach to the management of human activities whilst enabling the sustainable use of marine goods and services. It seeks to achieve or maintain good environmental status in the marine environment and prevent subsequent deterioration."*
>
> *(Ecosystem approach to management/Ecosystem Based Management (EBM): "a strategy for integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way.")*

The MSFD constitutes the vital environmental component of the union's maritime policy, designed to achieve the full economic potential of oceans and seas in harmony with the marine environment; and aims to achieve healthy marine waters by 2020 (Europa, 2011b).

The MSFD establishes European Marine Regions on the basis of geographical and environmental criteria. The marine strategies to be developed by each member state must contain a detailed assessment of the state of the marine environment, a definition of "Good Environmental Status" (GES) at regional level and the establishment of clear environmental targets and monitoring programmes (Europa, 2011b).

To reach the 2020 target, the Secretary of State (SoS) must carry out an assessment of the marine waters (including an economic and social analysis of the use of those waters and the cost of degradation of the marine environment) by 15th July 2012. The SoS must also periodically review and update the results of the assessment every 6 years. This assessment will also involve the setting of environmental targets and indicators; and the determination of Good Environmental Status (GES). Monitoring of the marine environment will commence in July 2014 and a programme of measures will be implemented between 2015 and 2016. The first review of the assessment of marine waters, GES indicators and targets will be undertaken in July 2018, with targets of GES reached by July 2020 (Europa, 2011b; DEFRA, 2011d; Matthisen, 2011).

Eleven descriptors have been identified and include, in brief (DEFRA, 2011b):

- **Biological diversity** is maintained. The quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic and climatic conditions.
- **Non-indigenous species** introduced by human activities are at levels that do not adversely alter the ecosystems.
- Populations of all commercially exploited **fish and shellfish** are within safe biological limits, exhibiting a population age and size distribution that is indicative of a healthy stock.
- All elements of the **marine food webs**, to the extent that they are known, occur at normal abundance and diversity and levels capable of ensuring the long-term abundance of the species and the retention of their full reproductive capacity.
- Human induced **eutrophication** is minimised, especially adverse effects thereof, such as losses in biodiversity, ecosystem degradation, harmful algae blooms and oxygen deficiency in bottom waters.
- **Sea-floor integrity** is at a level that ensures that the structure and functions of the ecosystems are safeguarded and benthic ecosystems, in particular, are not adversely affected.
- **Permanent alteration of hydrographical conditions** does not adversely affect the marine ecosystems.
- Concentrations of **contaminants** are at levels not giving rise to pollution effects
- **Contamination of fish, shellfish and other seafood for human consumption** do not exceed levels established by Community legislation of other relevant standards.
- Properties and quantities of **marine litter** do not cause harm to the coastal and marine environment.
- **Introduction of energy (e.g. underwater noise)**, is at levels that do not adversely affect the marine environment.

DEFRA have provided high level definitions of what GES will mean for UK marine waters (Matthisen, 2011):

- Ecologically diverse and dynamic seas which are clean, healthy and productive;
- Use is at a sustainable level;

- Fully functioning and resilient ecosystem;
- Biodiversity decline is prevented, biodiversity is in balance and protected;
- Hydro-morphological, physical and chemical state support the above; and
- No pollution effects.

A list of initial monitoring and measures to achieve GES were presented by DEFRA at the 2010 Coastal Futures conference. These are outlined in Table A.2 below:

Table A.2: Initial monitoring and measures to achieve Good Environmental Status

Descriptor	**Initial monitoring identified**	**Suggested Measures to achieve GES**
Biodiversity, sea-floor integrity, food webs	Substrate type; O2 concentration; species composition; contaminant status; size composition; trophodynamics; productivity; life history traits; bioengineers	Use Natura 2000 and MCZs to protect nationally rare/scarce/threatened/declining species/ habitat; protect impacted seabed (freeze footprint)
Non-indigenous species	Abundance; distribution; impact on ecosystem functioning	Ratify Ballast Water Management Convention; progress EU strategy in Invasive Alien Species (2008), i.e. prevention on eradication
Eutrophication	Water clarity; primary production; algae community; oxygen depletion	Use WFD CIS and OSPAR comp. Procedure
Commercial	F<Fmsy and SSB>SSBpa for 100% of assessed stocks; F<Fmsy and SSB>SSBmsy for a proportion; track size range (and trends for those without analytical assessment)	Use CFP and reform process
Contaminant pollution effects; Contaminants in food	Concentrations (list to be developed) and pollution effects from ecotox data	Follow OSPAR (below threshold levels); European Food Safety Authority etc., advice and regulations
Marine Litter	Litter on beaches; in water column/seafloor; in seabirds; microplastics	Develop risk-based methods to assess social, economic and ecological harm
Energy (underwater noise)	Low and mid-frequency impulsive sounds; high frequency impulsive sounds; low frequency continuous sound (ships) (EM; heat)	Some measures already in place (seismic, pile-driving seasonal restrictions)

Source: (Rogers, 2010)

DEFRA have expressed that it is intended for the MSFD to link into other policies including:

- Common Fisheries Policy
- EU Birds and Habitats Directive
- EU Water Framework Directive

- Marine Acts (including marine plans and Marine Conservation Zones (MCZ))

The MSFD will be complementary to, and provide the overarching framework for these key European and UK Directives and legislations, and will also help to fulfil international commitments undertaken at the World Summit on Sustainable Development and under the Convention on Biological Diversity and the OSPAR Convention (JNCC, 2011a).

Formal consultation on MSFD initial assessment and GES targets and indicators is planned for Autumn/Winter 2011. In Scottish waters Marine Scotland will have the devolved responsibility to provide the assessments of GES, but the working groups will work closely with DEFRA and other European and non-European countries sharing a marine region to ensure that the marine strategies are cohesive (Europa, 2011a; DEFRA, 2011d; Matthisen, 2011).

A.1.4 UK Marine Science Strategy

The UK Marine Science Strategy (MSS) sets the general direction of travel for the future of marine science across the UK between 2010 and 2025; and sets out three high level priority areas, with a number of related issues:

- Understanding how the marine ecosystem functions
    - Role of biodiversity
    - Recovery from disturbance
    - Assessment of GES using natural, social and economic sciences
    - Effects of human activities
- Responding to climate change and its interaction with the marine environment
    - Impact of oceanographic changes on marine ecosystems and feedbacks
    - Effects of acidification on marine organisms
    - Mitigation potential and adaptation, e.g. to protect life
    - Implications of natural variability
    - Introduction of alien species
- Sustaining and increasing ecosystem benefits
    - Understanding ecosystem services provided by the marine environment and human behaviour in relation to them
    - Biodiversity impacts of renewable energy
    - Conservation using tools such as Marine Protected Areas (MPAs)

- Cumulative effects of multiple human activities
- Predicting ecological impact of policy options

Within the framework of marine planning there is a range of EBM tools for conservation and other benefits, including creation of MPAs; and evidence is needed to establish which tools are appropriate in particular situations. E.g. there is a need to understand how the location, geographical extent and connectivity of key habitats and species may impact on their conservation needs and therefore on the choice of EBM tools best suited to protect and enhance them (Scottish Government, 2010).

A.1.5 UK Biodiversity Action Plan

The UK Biodiversity Action Plan (BAP) was published in 1994 as a response to the Convention on Biological Diversity (CBD) which the UK signed in 1992 in Rio de Janeiro. The CBD called for the development and enforcement of national strategies and associated action plans to identify, conserve and protect existing biological diversity, and to enhance it wherever possible (JNCC, 2011d).

The UK BAP describes the biological resources of the UK and provides detailed plans for conservation of these resources at national and devolved levels. The species and habitat considered to be of conservation concern were given the term ‘priority species’ and ‘priority habitats’; and from the initial list of species and habitats, 391 Species Action Plans (SAPs) and 45 Habitat Action Plans (HAPs) were published, although the list of SAPs, grouped SAPs and species statements, is reported to be 577 (JNCC, 2011d).

A requirement of the UK BAP is to provide three- or five-yearly reporting on the status of the action plans in order to provide information on status, trends, knowledge, progress against targets, threats and constraints. There have been four reporting cycles since the creation of the UK BAP (JNCC, 2011d).

A.1.6 Habitats Directive

Council Directive 92/43/EEC on the Conservation of natural habitats and of wild fauna and flora, also known as the ‘Habitats Directive’ was adopted in 1992 and was the European Union’s method of meeting obligations outlined under the Bern Convention (The Convention on the Conservation of European Wildlife and Natural Habitats, 1979). The Habitats Directive is transposed into UK Law through the Conservation (Natural Habitats, & c.) Regulations 1994 (which applies to land and territorial waters out to 12 nautical miles); and for UK offshore waters (12nm from the coast to 200nm), through the Offshore Marine Conservation (Natural Habitats & c.) Regulations 2007 (as amended). From April 2010 the Conservation of Habitats and Species Regulations 2010 (hereafter referred to as 'the Habitats Regulations') replaced The Conservation (Natural Habitats, &c.) Regulations 1994 (as amended) in England and Wales.

The Conservation of Habitats and Species Regulations 2010 (which are the principal means by which the Habitats Directive is transposed in England and Wales) update the legislation and consolidate all the many amendments which have been made to the regulations since they were first made in 1994. The new regulations do not make any substantive changes to existing policies and procedures, but do make new provisions designated to implement aspects of the Marine and Coastal Access Act 2009 ("The Marine Act") (see Section 2.4.2). These provisions provide for (JNCC, 2011c; SNH, 2011a):

- The transfer of certain licensing functions from Natural England to the Marine Management Organisation; and
- Marine Enforcement Officers to use powers under the Marine Act to enforce certain offences under the Habitats Regulations.

The main aim of the Habitats Directive is to maintain or restore natural habitats and wild species listed on the annexes to the Directive at a 'favourable' conservation status[8], introducing robust protection for those habitats and species of European importance; taking into account economic, social and cultural requirements (JNCC, 2011c).

The Habitats Directive includes a requirement to establish a European network of important, high quality conservation sites that will make a significant contribution to conserving the habitat and species identified in Annexes I and II of the Directive respectively. The regulations provide for the designation and protection of 'European sites'; the protection of 'European protected species'; and the adaption of planning and other controls for the protection of European Sites (JNCC, 2011c).

The regulations place a duty on the Secretary of State to propose a list of these sites based on their importance for either habitats or species (listed in Annexes I and II of the Habitats Directive respectively) to the European Commission. Once it is agreed that the sites submitted are considered worthy of designation, they are identified as Sites of

[8] Favourable Conservation Status as outlined in Articles 1 and 2 of the Habitats Directive.

Community Importance (SCIs). The sites are then designated as Special Areas of Conservation (SACs) within six years. The regulations also require the compilation and maintenance of a register of European sites, to include SACs and Special Protection Areas (SPAs) classified under Council Directive 79/409/EEC on the Conservation of Wild Birds (the Birds Directive). These sites form a network termed Natura 2000 (JNCC, 2011c).

The UK government classifies the sites prior to submission to the European Commission, based on their progression through the designation process. These progression classifications are listed below.

Draft SACs (dSAC):	Areas that have been formally advised to UK government as suitable for selection as SACs, but have not been formally approved by government as sites for public consultation.
Possible SACs (pSAC):	Sites that have been formally advised to UK Government, but not yet submitted to the European Commission.
Candidate SACs (cSAC):	Sites that have been submitted to the European Commission, but not yet formally adopted. Candidate SACs will be considered in the same way as if they had already been classified or designated, and any activity likely to have a significant effect on a site must be appropriately assessed. A site remains a cSAC until it has been formally designated as a SAC by UK Government, following approval as a Site of Community Importance (SCI) by the European Commission.

Of the 78 Annex I Habitats listed within the UK, 15 are considered to be 'Marine, coastal and halophytic' habitats. These habitats include (habitats highlighted bold also occur in offshore waters) (JNCC, 2011c):

- **Sandbanks which are slightly covered by sea water all the time**
    - JNCC describe Sandbanks as consisting of: *"sandy sediments that are permanently covered by sea water, typically at depths of less than 20m below chart datum (but sometimes including channels or other areas greater than 20m deep). The habitat comprises distinct banks (i.e.*

elongated, rounded or irregular 'mound' shapes) which may arise from horizontal or sloping plains of sandy sediment" (JNCC, 2011b).

- Estuaries
- Mudflats and sandflats not covered by seawater at low tide
- Coastal lagoons
- Large shallow inlets and bays
- **Reefs**
    - JNCC describe reefs as: *"rocky marine habitats or biological concretions that rise from the seabed. They are generally subtidal but may extend as an unbroken transition into the intertidal zone, where they are exposed to the air at low tide. Reefs are very variable in form and in the communities that they support. Two main types of reef can be recognised: those where animal and plant communities develop on rock or stable boulders and cobbles, and those where structure is created by the animals themselves (biogenic reefs)*" (JNCC, 2011b).
- **Submarine structures made by leaking gases**
    - The European commission describe this Annex I habitat as: *"Spectacular submarine complex structures, consisting of rocks, pavements and pillars up to 4 m high. These formations are due to the aggregation of sandstone by a carbonate cement resulting from microbial oxidation of gas emissions, mainly methane. The methane most likely originated from the microbial decomposition of fossil plant materials. The formations are interspersed with gas vents that intermittently release gas. These formations shelter a highly diversified ecosystem with brightly coloured species"* (European Commission, 2003).
- Annual vegetation of drift lines
- Perennial vegetation of stony banks
- Vegetated sea cliffs of the Atlantic and Baltic coasts
- *Salicornia* and other annuals colonising mud and sand
- *Spartina* swards (*Spartinion maritimae*)
- Atlantic salt meadows (*Glauco-Puccinellietalia maritimae*)
- Inland salt meadows
- Mediterranean and thermo-Atlantic halophilous scrubs (*Sarcocornetea fruticosi*)

A.1.7 Marine and Coastal Access Act 2009

The Marine and Coastal Access Bill ("The Marine Bill") gained royal assent on the 12th November 2009, thereby becoming an Act ("The Marine Act"). The aim of the Act is to introduce a new planning system for the marine environment, improve and simplify arrangements for managing marine development and ensure greater protection for the marine environment and biodiversity, and provide greater recreational access to the coast.

The Marine and Coastal Access Act 2009 is responsible for nine key areas of interest, including:

- The Marine Management Organisation;
- Marine Planning;
- Marine Licensing;
- Marine Nature Conservation;
- Fisheries Management and Marine Enforcement;
- Environmental Data and Information;
- Migratory and Freshwater Fisheries;
- Coastal Access; and
- Coastal and Estuary Management.

The elements of the Marine Act will come into force gradually through a series of detailed regulations and orders. Some of the first parts to be implemented are marine planning (summer 2010), nature conservation (2011/2012), marine licensing (spring 2011) and coastal access plans.

Provisions in Part 5 of the Marine and Coastal Access Act will enable Ministers to designate a new type of marine protected area, Marine Conservation Zones (MCZs). The MCZs will exist alongside the existing European marine sites (SACs and SPAs), to form a marine protected areas network. MCZs will be used to protect areas that are important to conserve the diversity of rare, threatened and representative habitats, species and geology, which will mostly be features not already covered by the European marine sites. Sites will be designated by 2012 on a regional basis through a stakeholder-led process, the selection process take into consideration socio-economic and well as ecological and geological concerns.

A.1.8 Marine (Scotland) Act 2010

The Marine (Scotland) Act (which applies to Scottish territorial waters only) introduces new powers relating to functions and activities in the Scottish marine area, including provisions concerning marine plans, licensing of marine activities, the protection of the area and its wildlife including seals, and regulation of sea fisheries; and comprises six key elements: the formation of Marine Scotland, a strategic marine planning system, a streamlined marine licensing system, improved marine nature conservation measures, improved measures for the protection of seals and improved enforcement measures (JNCC, 2011d).

A.1.9 The Water Framework Directive

In December 2003, the EC Water Framework Directive was transposed into national law by means of the Water Environment (Water Framework Directive; WFD) (England and Wales) Regulations, 2003. These regulations provide for the implementation process of the WFD from designation of all surface waters (rivers, lakes, transitional (estuarine) and coastal waters and groundwaters) as water bodies to achieving good ecological status by 2015. Unlike the EU Birds and Habitats Directives, which apply only to designated sites, the WFD applies to all water bodies, including those that are man-made.

There is currently no classification system in force for coastal waters, however classification schemes for both estuarine and coastal waters out to 1 nautical mile are being developed in response to the Water Framework Directive (WFD). This will replace the classification scheme discussed above and will assess a much wider range of pressures impacting on the marine environment. The schemes will classify the status of transitional and coastal waters using information on the ecological, chemical and hydromorphological quality of a body of water.

The WFD specifies the factors, referred to as quality elements that must be used in determining the ecological status or ecological potential and the surface water chemical status of a surface waterbody. The lists of quality elements for each surface water category are divided into three groups of elements:

- biological elements
- hydromorphological elements
- chemical and physico-chemical elements.

A.1.10 Common Fisheries Policy

The object of the Common Fisheries Policy (CFP) is to guarantee sustainable exploitation of living aquatic resources, and covers the conservation, management and exploitation of marine resources, and the processing and marketing of fishery and aquaculture products (Europa, 2011a).

The most important areas of action of the common fisheries policy are (Europa, 2011a):

- Laying down rules to ensure Europe's fisheries are sustainable and do not damage the marine environment
- Providing national authorities with the tools to enforce these rules and punish offenders
- Monitoring the size of the European fishing fleet and preventing it from expanding further
- Providing funding and technical support for initiatives that can make the industry more sustainable
- Negotiating on behalf of EU countries in international fisheries organisations and with non-EU countries around the world
- Helping producers, processors and distributors get a fair price for their produce and ensuring consumers can trust the seafood they eat
- Supporting the development of a dynamic EU aquaculture sector (fish, seafood and algae farms)
- Funding scientific research and data collection, to ensure a sound basis for policy and decision making.

The CPF is currently under reform after a Green Paper analysed the shortcomings of the current policy in 2009. The new policy package aims to be adopted and enter into force by 1st January 2013. The reformed policy aims to provide sustainability and long-term rather than short-term solutions. The new proposal sets out the following elements (Europa, 2011c):

- All fish stocks will have to be brought to sustainable levels by 2015, which is in line with the commitments the EU has undertaken internationally.
- An ecosystem approach will be adopted for all fisheries, with long-term management plans based on the best available scientific advice.

- The waste of food resources and the economic losses caused by throwing unwanted fish back into the sea ("discarding") will be phased-out. Fishermen will be obliged to land all the fish that they catch.
- The proposals also include clear targets and timeframes to stop overfishing; market-based approaches such as individual tradable catch shares; support measures for small-scale fisheries; improved data collection; and strategies to promote sustainable aquaculture in Europe.
- Consumers will be able to get better information on the quality and sustainability of the products they buy.
- General policy principles and goals will be prescribed from Brussels, while Member States will have to decide and apply the most appropriate conservation measures. In addition to simplifying the process, this will favour solutions tailored to regional and local needs.
- Operations throughout the fishing sector will have to make their own economic decisions to adapt fleet size to fishing possibilities. Fishermen's organisations will play a stronger role in steering market supply and increasing fishermen's profits.
- Financial support will only be granted to environmentally-friendly initiatives contributing to smart and sustainable growth. A strict control mechanism will rule out any perverse funding of illicit activities or overcapacity.
- Within international bodies and in its relations with third countries, the EU will act abroad as it does at home and promote good governance and a sound management of the sea in the rest of the world.

Throughout its history, the CPF has moved from focussing on increasing productivity and better standards of living for collective farmers and fishermen (as part of the Common Agricultural Policy) between 1957 and 1982, through a number of modifications and reforms which has led to the more precautionary principle for the protection and conservation of fishing resources that is seen today (Suris-Regueiro *et al.*, 2011).

A.2 Marine Spatial Planning

Marine Spatial Planning (MSP) is defined by UNESCO as:

> "*A public process of analysing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic and social objectives that usually have been specified through a political process.*"

Within the Marine (Scotland) Act 2010, a new legislative and management framework for the marine environment was created in order to manage the competing demands for the use of the sea; whilst also protecting the marine environment. This was addressed under Part 3 of the Act and places duty on the Scottish Ministers to prepare and adopt a National Marine Plan, followed by regional marine plans (Scottish Government, 2011).

In March 2011, the Scottish Government produced a pre-consultation draft of the National Marine Plan (NMP) (Scottish Government, 2011). This document was open for consultation until 7th June 2011 and will be followed by further consultation in 2011, with the final marine plan being delivered in Spring/Summer 2012. Table A.3 lists the main priorities and targets set within the National Marine Plan.

Table A.3: Main priorities for marine industries identified under the National Marine Plan

Marine Industries/Sectors	Main Priorities and/or Targets Set (if any)
Marine Environment	Achieve GES by 2020
Commercial fisheries	• Fish all stocks at Maximum Sustainable Yield • sustaining stocks • the industry and coastal communities
Wild salmon and freshwater fisheries	• Sustainably manage fisheries • Identify priority areas
Aquaculture	Increase finfish production by 50% and shellfish production by 100% by 2020
Oil and Gas	Deliver maximum value at minimal environmental cost
Carbon Capture and Storage	
Renewables	Provide 10 GW of capacity by 2020 in place and under construction
Tourism and Recreation	Enhance and develop opportunities for marine recreation
Marine Transport	• Deliver lifeline services • Protect the £1.5bn contribution of Scotland's ports to the Scottish economy • Ensure port facilities are available to support renewable and lifeline services • shipping, ports, harbours, aviation, ferries, Marine Coastguard Agency
Telecoms and cables	
Military activities	
Marine nature conservation	Sustainably manage our seas using a three pillar approach (species measures, site protection and wider seas measures, including marine planning and sectoral policies and other initiatives)
Marine historic environment	
Coastal protection and flood defence	Protect the coast against change and flooding
Water abstraction	Safeguard water resources
Waste water	Improve wastewater quality
Aggregates and disposal	

Source: (Harrald and Davies, 2010)

According to the Scottish Marine Bill Regulatory Impact Assessment, independently produced by ABP Mer (2009) on behalf of the Scottish Government, a statutory marine planning system would consist of three tiers which would provide for: international requirements under the European Marine Strategy Directive and OSPAR objectives; a national marine policy statement, objectives and a Scottish Marine Plan; and 9-13 local plans within Scottish Marine Regions.

A.3 Marine Protected Areas

Scottish Marine Protection Areas (MPAs) are a new national designation under the Marine (Scotland) Act for inshore waters and the Marine and Coastal Access Act 2009 for offshore waters, where Scottish Ministers have executive devolution of authority for the designation of MPAs for the conservation of important marine biodiversity and geodiversity out to 200 nautical miles.

Within the Marine Nature Conservation element, powers in the Marine (Scotland) Act enable Scottish Ministers to designate three types of Marine Protected Area (MPA) across Scottish territorial waters: Nature Conservation MPAs; Historic MPAs; and Research/Demonstration MPAs (JNCC, 2012b).

The Scottish MPA project has been established by Marine Scotland (Scottish Government), Scottish Natural Heritage (SNH) and the Joint Nature Conservation Committee (JNCC) to identify and recommend MPAs for the conservation of nationally important features of marine biodiversity and geodiversity to Government. Scottish MPAs will be identified using science-based selection criteria, but socio-economic information may be taken into account when selecting between sites of equal scientific merit and to identify likely management issues (Natural England, 2010).

The new MPA powers allows Scotland to contribute to the UK’s European and International marine conservation commitments, such as those laid out under the Marine Strategy Framework Directive, the OSPAR Convention and the Convention on Biological Diversity (JNCC, 2012b); with the government required by European law to introduce a network of MPAs by the end of 2012 (Natural England, 2010). No MPAs have yet been designated under the Marine (Scotland) Act.

A.4 Integrated Coastal Zone Management

On 30 May 2002, the European Parliament and Council Recommendation on Integrated Coastal Zone Management (ICZM) in Europe was adopted by the fifteen member states of the EU. The EU recommendation states that the process of developing an ICZM strategy should involve all interests and disciplines and promote the sustainable management of the coastal zone, by integrating social, economic and environmental interests (Cooper, 2011; O'Hagan and Ballinger, 2010).

The European Commission defines ICZM as (Wikipedia, 2011):

> *“a dynamic, multidisciplinary and iterative process to promote sustainable management of coastal zones. It covers the full cycle of information collection, planning (in its broadest sense), decision making, management and monitoring*

> *of implementation. ICZM uses the informed participation and cooperation of all stakeholders to assess the societal goals in a given coastal area, and to take actions towards meeting these objectives. ICZM seeks, over the long-term, to balance environmental, economic, social, cultural and recreational objectives, all within the limits set by natural dynamics. 'Integrated' in ICZM refers to the integration of objectives and also to the integration of the many instruments needed to meet these objectives. It means integration of all relevant policy areas, sectors, and levels of administration. It means integration of the terrestrial and marine components of the target territory, in both time and space."*

The principles of ICZM have been embedded throughout the development of the Marine and Coastal Access Act 2009 which provides an opportunity to join up marine management with the existing terrestrial management and planning strategies (DEFRA, 2011c). The EC principles of ICZM include (Ballinger *et al.*, 2010):

- Broad holistic approach
- Long-term prespective
- Local specificity
- Working with natural processes
- Adaptive management
- A combination of instruments
- Support and involvement of all stakeholders
- Participatory approach

Appendix B. Draft Priority Marine Features in Scottish Waters

Priority Marine Feature	Specific Important Biotopes and Species included within PMF	
	Common Name	Scientific/Biotope Name
Blue mussel beds	*Mytilus edulis* beds on reduced salinity infralittoral rock	IR.LIR.IFaVS.MytRS
Blue mussel beds	*Mytilus edulis* beds on sublittoral sediment	SS.SBR.SMus.Mytss
Blue mussel beds	Intertidal *Mytilus edulis* beds on mixed and sandy sediments	LS.LBR.LMus.Myt
Blue mussel beds	*Mytilus edulis* and *Fabricia sabella* in littoral mixed sediment	LS.LSa.ST.MytFab
Burrowed mud	Sea-pen and burrowing megafauna communities	SS.SMu.CFiMu.SpnMeg
Burrowed mud	Burrowing megafauna and *Maxmuelleria lankesteri* in circalittoral mud	SS.SMu.CFiMu.MegMax
Burrowed mud	Tall sea pen	*Funiculina quadrangularis*
Burrowed mud	Amphipod	*Maera loveni*
Burrowed mud	Fireworks anemone	*Pachycerianthus multiplicatus*
Coldwater coral reefs.	*Lophelia* reefs	SS.SBR.Crl.Lop
Sea loch egg wrack beds	*Ascophyllum nodosum* ecad *mackayi* beds on extremely sheltered mid eulittoral mixed substrata	LR.LLR.FVS.Ascmac
Flame shell beds	*Limaria hians* beds in tide-swept	SS.SMx.IMx.Lim
Horse mussel beds	*Modiolus modiolus* beds with *Chlamys varia*, sponges, hydroids and bryozoans on slightly tide-swept very sheltered circalittoral mixed substrata	SS.SBR.SMus.ModCvar
Horse mussel beds	*Modiolus modiolus* beds with fine hydroids and large solitary ascidians on very sheltered circalittoral mixed substrata	SS.SBR.SMus.ModHAs
Horse mussel beds	*Modiolus modiolus* beds with hydroids and red seaweeds on tide-swept circalittoral mixed substrata	SS.SBR.SMus.ModT
Inshore deep mud with burrowing heart urchins	*Brissopsis lyrifera* and *Amphiura chiajei* in circalittoral mud	SS.SMu.CFiMu.BlyrAchi
Intertidal mudflats	Intertidal mudflats	LS.LMu
Kelp and seaweed communities on sublittoral sediment	Kelp and seaweed communities on sublittoral sediment	SS.SMp.KSwSS
Low or variable salinity habitats	Faunal communities on variable or reduced salinity infralittoral rock	IR.LIR.IFaVS
Low or variable salinity habitats	Kelp in variable or reduced salinity	IR.LIR.KVS
Low or variable salinity habitats	Submerged fucoids, green or red seaweeds (low salinity infralittoral rock)	IR.LIR.Lag
Low or variable salinity habitats	Sublittoral mud in low or reduced salinity (lagoons)	SS.SMu.SMuLS
Low or variable salinity habitats	Mollusc	*Hydrobia neglecta*
Low or variable salinity habitats	Bird`s nest stonewort	*Tolypella nidifica*
Low or variable salinity habitats	stonewort	*Chara baltica*
Low or variable salinity habitats	Foxtail stonewort	*Lamprothamnium papulosum*

Priority Marine Feature	Specific Important Biotopes and Species included within PMF	
	Common Name	**Scientific/Biotope Name**
Maerl beds	Maerl beds	SS.SMp.Mrl
Maerl or coarse shell gravel with burrowing sea cucumbers	*Neopentadactyla mixta* in circalittoral shell gravel or coarse sand	SS.SCS.CCS.Nmix
Native oyster beds	*Ostrea edulis* beds on shallow sublittoral muddy mixed sediment	SS.SMx.IMx.Ost
	Native oyster	*Ostrea edulis*
Northern seafan communities	Caryophyllia smithii and Swiftia pallida on circalittoral rock	CR.MCR.EcCr.CarSwi
	Mixed turf of hydroids and large ascidians with Swiftia pallida and Caryophyllia smithii on weakly tide-swept circalittoral rock	CR.HCR.XFa.SwiLgAs
	Northern sea fan	*Swiftia pallida*
Seagrass beds	*Zostera marina*/angustifolia beds on lower shore or infralittoral clean or muddy sand	SS.SMp.SSgr.Zmar
	Zostera noltii beds in littoral muddy sand	LS.LMp.LSgr.Znol
Serpula vermicularis reefs on very sheltered circalittoral muddy sand	*Serpula vermicularis* reefs on very sheltered circalittoral muddy sand	SS.SBR.PoR.Ser
Shallow tideswept coarse sands with burrowing bivalves	*Moerella* spp. with venerid bivalves in infralittoral gravelly sand	SS.SCS.ICS.MoeVen
Submarine structures made by leaking gases	Submarine structures made by leaking gases	No code
Tide-swept algal communities	Fucoids in tide-swept conditions	LR.HLR.FT
	Halidrys siliquosa and mixed kelps on tide-swept infralittoral rock and coarse sediment	IR.HIR.KSed.XKHal
	Kelp and seaweed communities in tide-swept sheltered conditions	IR.MIR.KT
	Laminaria hyperborea on tide-swept, infralittoral mixed substrata.	IR.MIR.KR.LhypTX

Source: (SNH, 2011b)

Priority Marine Feature (common name)	Taxon Group	Scientific Name
Burrowing sea anemone	Cnidarian	*Arachnanthus sarsi*
Pink soft coral/pink sea fingers	Cnidarian	*Alcyonium hibernicum*
White cluster anemone	Cnidarian	*Parazoanthus anguicomus*
Crayfish, crawfish, spiny lobster	Crustacean	*Palinurus elephas*
Feather star	Echinoderm	*Leptometra celtica*
Iceland cyprine	Mollusc	*Arctica islandica*
Fan mussel	Mollusc	*Atrina pectinata*
Heart cockle	Mollusc	*Glossus humanus*
Otter	Otter	*Lutra lutra*
Eastern Atlantic harbour seal/common seal	Seal	*Phoca vitulina*
Grey seal	Seal	*Halichoerus grypus*
Harbour porpoise	Cetacean	*Phocoena phocoena*

Priority Marine Feature (common name)	Taxon Group	Scientific Name
Minke whale	Cetacean	*Balaenoptera acutorostrata*
Killer whale	Cetacean	*Orcinus orca*
Short-beaked common dolphin	Cetacean	*Delphinus delphis*
Bottlenose dolphin	Cetacean	*Tursiops truncatus*
White-beaked dolphin	Cetacean	*Lagenorhynchus albirostris*
Risso's dolphin	Cetacean	*Grampus griseus*
European river lamprey (marine part of life cycle)	fish	*Lampetra fluviatilis*
Basking shark	fish	*Cetorhinus maximus*
Common skate species complex	fish	Formerly *Dipturis batis* now split provisionally into *D. cf. flossada* and *D. cf.intermedia*
Atlantic herring (juveniles and spawning adults)	fish	*Clupea harengus*
Atlantic salmon (marine part of life cycle)	fish	*Salmo salar*
Angler fish (juveniles)	fish	*Lophius piscatorius*
Cod	fish	*Gadus morhua*
Whiting (juveniles)	fish	*Merlangius merlangus*
Ling	fish	*Molva molva*
Saithe (juveniles)	fish	*Pollachius virens*
Norway pout	fish	*Trisopterus esmarkii*
Sandeel complex	fish	*Ammodytes marinus, Ammodytes tobianus*
Sand goby	fish	*Pomatoschistus minutus*
Atlantic mackerel	fish	*Scomber scombrus*
Eel (marine part of life cycle)	fish	*Anguilla anguilla*
Spiny dogfish	fish	*Squalus acanthias*

Source: (SNH, 2011b)

Note on the inclusion of commercially fished species

A small number of commercially fished species are included on the list of Priority Marine Features. Inclusion on the list is a way of flagging up the conservation importance of these species, but it does not necessarily mean that SNH will be responsible for delivering any management which may be required. For the commercial species, Marine Scotland will be the lead organisation responsible for management in the seas around Scotland. This will largely be through existing fisheries management measures, rather than specific conservation ones such as Marine Protected Areas (SNH, 2011b).

Appendix C. Strangford Lough – a case study of the loss and restoration of *Modiolus modiolus*

Modiolus modiolus beds have been documented in Strangford Lough since the mid-1800s and were known to be extensive in the 1970s (Roberts, 2003; Roberts *et al.*, 2011); although the full extent of the beds was not reported in detail until the early 1990, but which time certain areas, particularly those occupied by the *M. modiolus*/*Chlamys varia* community were heavily impacted by trawling for queen scallops (Roberts, 2003; Service and Magorrian, 1997). As a result of the damage caused to the biogenic reefs, seabed and associated epifauna, a number of legislative measures were introduced in 1993 by the then Department of Agriculture for Northern Ireland (now Department of Agriculture and Rural Development) to manage fishing activity (Roberts, 2003; Service and Magorrian, 1997).

Strangford Lough is currently listed as a cSAC under the EC Habitats Directive (92/43/EEC) based sublittoral *M. modiolus* biogenic reefs. Concern has been raised by a number of NGO's and governmental departments since 2002 over the state of these reefs (Roberts *et al.*, 2004). In 2003 as part of the Strangford Lough Ecological Change Investigation the status of the *Modiolus* beds (in terms of their extent, coherence and population structure, including associated communities) were investigated. The data collected were compared to data sets obtained by Queens University, Belfast; and published work held and undertaken by Ulster Museum throughout the 1970s and 80s (Roberts *et al.*, 2004).

During the survey, a total of 272 species were found living on or in the *Modiolus* reefs in Strangford Lough. In the North Basin, *Modiolus* communities are characterised by *Modiolus modiolus* co-dominant with *Chlamys varia* with abundant queen scallops and occurred between 10m and 35m depth (Roberts *et al.*, 2004). This biotope (SCR.MODCvar) is only known within Strangford Lough and possibly Loch Creran in SW Scotland, possibly demonstrating a fine balance of climatic conditions (Roberts *et al.*, 2004).

It is considered that the beds in the North Basin appear to be significantly reduced in extent compared to historical data and may no longer be in pristine condition. Surveys carried out between 1975 and 1985 indicated that the majority of the North Basin sites had clumped *Modiolus* communities. Now, for example, at the centre of the North

Basin, formerly the main area for the classic *Modiolus* with *Chlamys* biotope no clumped *Modiolus* remain; the area now has extensive areas of dead shell with occasional live *Modiolus* individuals. This site was previously zoned for trawling for queen scallops (Roberts *et al.*, 2004).

In the South Basin, the *Modiolus* community is characterised by less *Chalamys* or *Aeuipecten* then the North Basin, but more hydroids and brittlestars (SCR.MODHAs) in sheltered areas and MCR.ModT in tide-swept areas; and are considered to be less diverse than the *Modiolus/Chlamys* biotope. As this area has few *Chlamys* or *Aequipecten* it has not been subjected to the same trawling activities as the North Basin, however, the area is in a dredging zone for king scallops (Roberts *et al.*, 2004).

The condition of the *Modiolus* beds varied in the South Basin and in some areas including the Black Rock site, the beds were mostly intact, although the sites adjacent showed beds of poor condition, with many *Modiolus* having been buried by recently accumulated muddy sediment. The previously surveyed sites east of Selk Rock, which was reported to have a dense bed in 1976, now consist of mostly dead shells, with few live individual *Modiolus* (Roberts *et al.*, 2004).

Overall, the *Modiolus* community in both basins and the central channel had seen a significant reduction in their numbers and distribution; and as such, the *Modiolus* communities in Strangford Lough no longer meet the first and second criteria under the EU definition of favourable conservation status[9] and the *Modiolus* itself does not meet criteria three (Roberts *et al.*, 2004). The survey also reported that there is no evidence to suggest recovery of *Modiolus* communities in Strangford Lough has been taking place since the conservation measures (including legislation to manage fishing activity) were introduced in 1993 (Roberts *et al.*, 2004).

The restoration project outlined three objectives to restore the biogenic reef feature (SLRIG, 2005). These objectives are outlined below:

- Short term:

[9] EU definition of favourable conservation status for both the habitat and main characterising species: Criteria 1) Its natural range and areas it covers within that range is stable or increasing; Criteria 2) The specific structure and functions which are necessary for its long-term maintenance exist and are likely to continue to exist for the foreseeable future, and; Criteria 3) the conservation status of its typical species in favourable.

    - To identify, map and introduce total protection for the remaining *Modiolus* biogenic reef sites within 1 year of adoption of the plan; damaged biogenic reefs will also be identified and protected from further damage.
    - To assess whether conditions in appropriate areas within Strangford Lough are currently favourable for restoration using pilot scale translocation experiments

- Medium term:
    - To show, using appropriate reference and control sites, evidence of recovery of the *Modiolus* biogenic reef feature towards ‘Unfavourable Condition, Recovering’ within 5 years of initiation of the plan

- Long term:
    - To restore the Strangford Lough *Modiolus* biogenic reed feature to ‘Favourable Conservation Status’.

The 2011 published report (Roberts *et al.*, 2011) from the *Modiolus* Restoration Research Project reported the following key findings:

- *Changes in distribution, density and condition*: *Modiolus* beds can now be found in an area between Castle Island and Gransha Point in the north and Taggart Island and Kate’s Pladdy in the south. Beds considered in ‘good’ condition can be found at Craigyouran and Round Island pinnacle. Remaining beds are fragmented at patchy.
- *Small scale temporal and spatial variability*: Short term monitoring is of limited value in following temporal trends because there are significant interactions amongst variables.
- *Potential for natural recovery*: Suggests that the biotope in the north basin has continued to decline in condition since SLECI, whereas the biotope in the south basin appears to show increased fragmentation although some good condition sites remain.

The report states that in Strangford Lough, much of the degraded *M.* modiolus habitat lies within 10-15km of sources of propagules from the remaining beds; and this suggests that signs of natural recovery might be expected within 20 years, provided no further disturbances occur.

Appendix D.Potential impacts to *Modiolus modiolus* reefs as a result of the installation of renewable tidal energy devices

General Impact	Potential Impact Associated with Tidal Devices	Potential Impacts to *Modiolus modiolus* (not quantified)	Likelihood of impact occurring	Positive or Negative
Turbidity	Turbidity of the area may increase or decrease as a result of the placement of the tidal devices or as a result of a change to the current regime. Alteration to the turbidity may result in alteration of the biological and physical dynamics and characteristics of the area and may lead to the alteration of the areas biodiversity etc.	Increased turbidity may result in increased amounts of suspended sediment in the water column. *M. modiolus* are suspension feeders. This increase in suspended sediment could result in increased availability of food which could lead to increased populations or growth rates, but which could ultimately lead to greater food competition etc. Increased suspended sediment may result in altering their ability to filter feed – too much sediment to filter could block filters, or could impair their ability to filter out the food. Increased turbidity could also result in increased abrasion to the *M. modiolus* especially to areas of new or small areas of the mussels; where there has been less time to develop protection around the basal attachments.		+ve/-ve -ve -ve
Currents	The placement of the tidal device structures may alter the tidal currents in the area of the device both in the water column and at the seabed.	Increased currents may result from the movement of the tidal device/turbine in the water column. Decreased currents may result from the tidal device/turbine removing energy from the water column. This would lead to various other issues include providing the reefs adjacent to the tidal array with less food as the currents are not as strong as previously measured. This could lead to food availability impacts to the reef and associated organisms, ultimately altering the biodiversity dynamics etc.		-ve +ve +ve/-ve

General Impact	Potential Impact Associated with Tidal Devices	Potential Impacts to *Modiolus modiolus* (not quantified)	Likelihood of impact occurring	Positive or Negative
		Decreased currents may also create better environmental conditions for *Modiolus* to settle out and create reefs. Altered direction of currents may result from the placement of tidal device in the tidal stream. The current may hit the device and split to form to tidal streams, that may create different tidal circulations which could hinder food availability etc, however may create a more suitable settlement environment.		
Substratum Loss	Substratum loss may occur as a result of construction works – particularly when sediments are released into the current and carried by the current and deposited elsewhere.	Sediment loss in the area of a Modiolus reefs could lead to the reef becoming destabilised and damage could occur to the overall reef structure. *Modiolus* attach themselves to hard substrates, if sediment loss occurs, this could result in the exposure of hard substrates which may allow for additional attachment surfaces.		-ve +ve
Sedimentation	Sedimentation may occur in areas away from the tidal device – sediment could be lifted and deposited elsewhere due to construction activities and/or as a result in a change to the turbidity and/or current regime.	Aggregation of sediments may allow reefs to continue to build, and potential become stronger. The sediment may be caught in the basal attachments of the organisms and provide additional strength and stability. Sedimentation may to lead to excessive and continued build-up of sediment away from the tidal devices and over the reef area – this could lead to burial of the reef and the associated organisms. See 'smothering'. Excessive sedimentation may also lead to a change in the biodiversity of the reef – with the smothering of non-motile associated		+ve -ve -ve -ve

General Impact	Potential Impact Associated with Tidal Devices	Potential Impacts to *Modiolus modiolus* (not quantified)	Likelihood of impact occurring	Positive or Negative
		organisms and loss of motile organisms that leave the reef area. A build-up of sediment over areas of hard substrate may lead to a loss of attachment surface for the *Modiolus* which may lead to a loss of future reef structures. Sediment contaminants may be leached as a result of disturbance making them readily available to be taken up by filter feeders as the sediment settles out over the reefs and surrounding areas, or as it is released into the environment. However, these could lead to better sediment nourishment.		+ve/-ve
Smothering	Seabed smothering may occur as a result of sedimentation away from the tidal devices, or at the site of the tidal device as a result of a change to the tidal regime and/or turbidity etc. Smothering may alter the benthic and epibenthic community, especially of sessile organisms.	Smothering, brought about by the settling out of suspended sediment particles may lead to decreased growth rates due to the lack of oxygen Their ability to filter feed would be hindered as the sediment becomes too deep for the *Modiolus* to feed or their gills become clogged with the sediment again leading to decreased growth rates or death. Smothering may lead to asphyxiation and death of the *Modiolus* and any other non-motile associated organisms. Smothering may also lead to a change in biodiversity of the reefs as motile organisms leave or organisms are killed through asphyxiation or lack of food. Sediment contaminants (see above)		-ve -ve -ve -ve +ve/-ve
Food Availability	Altered food availability as a result of the presence or construction of the tidal devices.	Decrease in food could occur as a result of smothering, sedimentation, decreased		-ve

General Impact	Potential Impact Associated with Tidal Devices	Potential Impacts to *Modiolus modiolus* (not quantified)	Likelihood of impact occurring	Positive or Negative
		turbidity or a change in current regime (see above). Increase in food could occur as a result of increased turbidity or a change in current regime (see above) Food availability could also be altered by a change in the biodiversity dynamics of the environment. For example an increase in associated organisms could lead to increased competition for food.		+ve +ve/-ve
Predation	Altered predation patterns as a result of the placement of the tidal devices.	As a result of a number of factors, as described above, predation may be decreased in the vicinity and adjacent to the tidal array. This decrease may be a result of altered currents and turbidity, reduction of reef habitat or a change in the biodiversity dynamics of the area. Decreased predation may allow the reef structures to increase, however decreased predation may also lead to a decline in reef structure if the biodiversity dynamics are altered. Increase in predation may occur as a result in the current regime, or		+ve/-ve
Habitat	The placement of the tidal devices will create new habitat or alter existing habitat types in the area.	Loss of habitat may be caused by sedimentation in the vicinity and adjacent to the area of the tidal array. Soft sediments settling on hard substrate may reduce the locations that modiolus could settle.	**Low** – given the tidal velocities required for tidal devices – it is unlikely that enough sedimentation will occur to dramatically reduce the amount of available attachment	-ve +ve

General Impact	Potential Impact Associated with Tidal Devices	Potential Impacts to *Modiolus modiolus* (not quantified)	Likelihood of impact occurring	Positive or Negative
		Creation of artificial habitat will occur when the tidal devices are placed in the water column. This will be particularly significant if it is placed in an area of predominantly soft sediments – where *Modiolus* is unlikely to occur without the aid of an artificial structure.	surfaces within the immediate area of the tidal array and surrounding environment. **High** – the tidal devices will create an artificial substrate that may ultimately be a suitable settlement site for *Modiolus*.	
Physical Disturbance	Physical disturbance may relate to the impacts discussed above, but will also include physical removal of any reef area to make room for tidal device placement.	Once the tidal devices are placed in the water column and on the seabed bed – the impacts to *Modiolus* are likely to be limited to a change in current regime or habitat loss/creation. (see above) If areas of reef are removed to allow placement of the devices, this may result in loss of the reef and associated organisms – further work is required to determine the impacts of removing and replanting *Modiolus*.		
Physical Presence	The tidal device gravity base structures for example, would be placed on or buried within the sediment and	Once the tidal devices are placed in the water column and on the seabed bed – the impacts to *Modiolus* are likely to be limited to a change in current regime or habitat loss/creation. (see above)		
Scouring	Scouring may occur at the base of the tidal devices, resulting in sediment loss and sediment suspension.	Scouring will be limited to the immediate vicinity of the tidal device. Scouring may increase turbidity in the area (see above).		
Anchoring	Anchoring of the tidal devices	Anchoring of the tidal device may impact on habitat availability.		

Source: Author’s own* [*Based on methodologies and industry EIA guidelines e.g. (CEFAS, 2004)]

Appendix E. Data Formatting and Processing

A number of online data sources were identified from a thorough internet search of online species databases and other websites. Data sources were only used were they were identified as containing enough information on sample location, specifically Longitude and Latitude data. Of the many internet sites investigated for species distribution information, only four were identified as containing suitably robust species distribution data. These sources are listed and compared in Table E.1. An overview of the identified databases is outlined below.

Initially the search for species distribution data was focussed on the distribution of the horse mussel *Modiolus modiolus*. The 2012 distribution data for *M. modiolus* beds/reefs were collated from the Joint Nature Conservation Committee (see Table E.1 below).

Table E.1: Data Sources

Website	Link	Reference
EuroOBIS	http://www.marbef.org/data/eurobissearch.php	(Flanders Marine Institute, 2004)
National Biodiversity Network (NBN) Gateway	http://data.nbn.org.uk/	(NBN, 2011)
Marine Recorder	http://esdm.co.uk/MarineRecorder/index.html	(JNCC, 2008)
Irish Catalogue	http://www.habitas.org.uk/nmi_catalogue/index.html	(Nunn and Holmes, 2005)
MESH **MESH Atlantic**	http://www.searchmesh.net/default.aspx?page=1974&&mapInstance=MESHAtlanticMap_&Layers=OSPARhabPoints	(MESH; http://www.searchmesh.net)

Institution	Details
Natural History Museum	Time was spent retrieving *M. modiolus* specimens from wet and dry archive storage. All details contained on the specimen label were catalogued and entered into an Excel spreadsheet.
National Museum of Scotland	
National Museum of Ireland	All records of *M. modiolus* have been previously catalogued and were included in the online Irish Catalogue. This data was extracted from the online document and entered in the spreadsheet.
National Museums Northern Ireland	Curator, Julia Nunn advised that all records had been included in the Irish Catalogue. In addition, she provided her personal records. The records were transcribed from the scanned document and entered into the spreadsheet.
Centre for Environment, Fisheries and Aquaculture Science	*M. modiolus* presence records were provided by Roger Coggan from CEFAS's Unicorn Database.
Marine Scotland	Marine Scotland advised that data held by these institutions had been submitted to SNH for use in the Marine Protected Areas (MPAs) project or was available on EurOBIS or NBN Gateway
Scottish Association of Marine Science	
Scottish Natural Heritage	Provided information on the location of *M. modiolus* bed distribution. This Data is currently being used to identify suitable MPA sites.

EurOBIS

The European Ocean Biogeographic Information System (EurOBIS) is an integrated data system developed by the Flanders Marine Institute (VLIZ) for the EU network of Excellence "Marine Biodiversity and Ecosystem Functioning" (MarBEF[†††]) in 2004. The main aim of which is to centralise biogeographic data on marine species collected by European institutions and to ensure that data is quality controlled, easily accessible and freely available. Datasets gathered for input into the system undergo a series of quality control procedures before integration into the online database. The database provides information on taxonomy, temporal and spatial distribution of species which can be downloaded for analysis. The data system therefore provides for a better understanding of long-term, large-scale patterns within European marine waters (Flanders Marine Institute, 2004).

EurOBIS is the European node of the Ocean Biogeographic Information system (OBIS) which provides similar global data collaboration within the wider scientific community which ultimately aids rapid access to data on marine species distribution, and ocean environmental data; and therefore enables study of patterns of species distribution on a larger scale (Flanders Marine Institute, 2004).

National Biodiversity Network Gateway and Marine Recorder

The National Biodiversity Network (NBN) is a collaborative partnership between a number of the UK's nature conservation organisations, such as: the Department of the Environment, Food and Rural Affairs (DEFRA), Biological Records Centre, Centre for Ecology and Hydrology etc, and over 140 data contributors, e.g. Marine Conservation Society, the National Trust, and the Environmental Agency etc (NBN, 2011).

The NBN Gateway is essentially a "data warehouse" which can be accessed online and pulls together biodiversity information collated by the many contributors; and provides distribution data of particular species (terrestrial, freshwater and marine) which can be downloaded and analysed (NBN, 2011).

[†††] MarBEF is a network of excellence funded by the EU and consisting of 94 European marine institutes and is used as a platform to integrate and disseminate knowledge and expertise on marine biodiversity. A key task of MarBEF is the integration of different resources and datasets relating to marine biodiversity.

Marine recorder was developed as a user interface connection for the NBN gateway allowing users to input and export marine benthic biological data.

Irish Catalogue

The Catalogue of the Irish and British Marine Mollusca in the collections of the National Museum of Ireland – Natural History 1835 – 2008 (Nunn and Holmes, 2005) provides curatorial information on molluscan specimens collections (including *Modiolus modiolus*) held at the National Museum of Ireland. This data was catalogued and transferred into an electronic format which is available on the internet. Specimens can be searched for, and information downloaded.

MESH

The distribution of OSPAR Threatened and/or Declining Species and Habitats (Priority Marine Habitats or Priority Marine Features) has been compiled and mapped by the Joint Nature Conservation Committee. Distribution of *M. modiolus* beds were downloaded from the MESH website.

The MESH (Mapping European Seabed Habitat) website provides an interactive mapping portal designed to give easy access to a catalogue of marine data. The MESH Project ran between 2004 and 2008 and consisted of a consortium of twelve partners from five European countries led by the UK's Joint Nature Conservation Committee (JNCC), with financial support from the EC's INTERREG IIIB NWE Programme. The mapping section of the website continues to be updated with the best available seabed-habitat data.

Museum Cataloguing

Contact was made with the Mollusc curators at the Museum of Natural History, London; the National Museum of Scotland, Edinburgh; the National Museums Northern Ireland, County Down; and the National Museum of Ireland, Dublin. In addition, data requests were submitted to Marine Scotland, Scottish Natural Heritage (SNH), the Scottish Association of Marine Science (SAMS), and the Centre for Environment, Fisheries and Aquaculture Science (CEFAS).

As expected very few specimen archives had been catalogued at the museums.

A.5 Methods: Formatting and Processing of Data

Given the overlap of a number of the online and offline data sources, it was necessary to carry out some data re-formatting, manipulation and deletion of duplicate entries.

All coordinates were converted to WGS 1984 decimal degrees, to three decimal points. The following conversion formulas were applied:

- **Degrees and Minutes to Decimal Degrees:**
  - **Latitude:** $\sum Degrees + \left(Minutes * \frac{1}{60}\right)$
  - **Longitude:** $\sum Degrees + [0 - \left(Minutes * \frac{1}{60}\right)]$
- **OS Grid Reference to Decimal Degrees:**
  - Conversion code in Excel format provided by Brady (2008)

Once conversions had been carried out, all data sources were compiled into a new spreadsheet, the data was sorted and any duplicates (based on three decimal places) removed.

A.5.1 "Presence and Absence" Data Collection

Unlike the presence only data collection, data on the presence and absence of *M. modiolus* proved harder to locate. The majority of online databases only allowed the user to search for information on the location of a particular species at a single site rather than distinguishing between actual surveys transects, despite the information technically being available behind the scenes of the database.

A number of surveys/datasets were identified in the EurOBIS database that may potentially have records of *M. modiolus*, a list of which is shown in Table E.2. These surveys/datasets were chosen based on their location in relation to know geographic distribution of *M. modiolus*. A request was submitted to the data managers at VLIZ for this data. Figure E.1 illustrates a typical survey transect. .

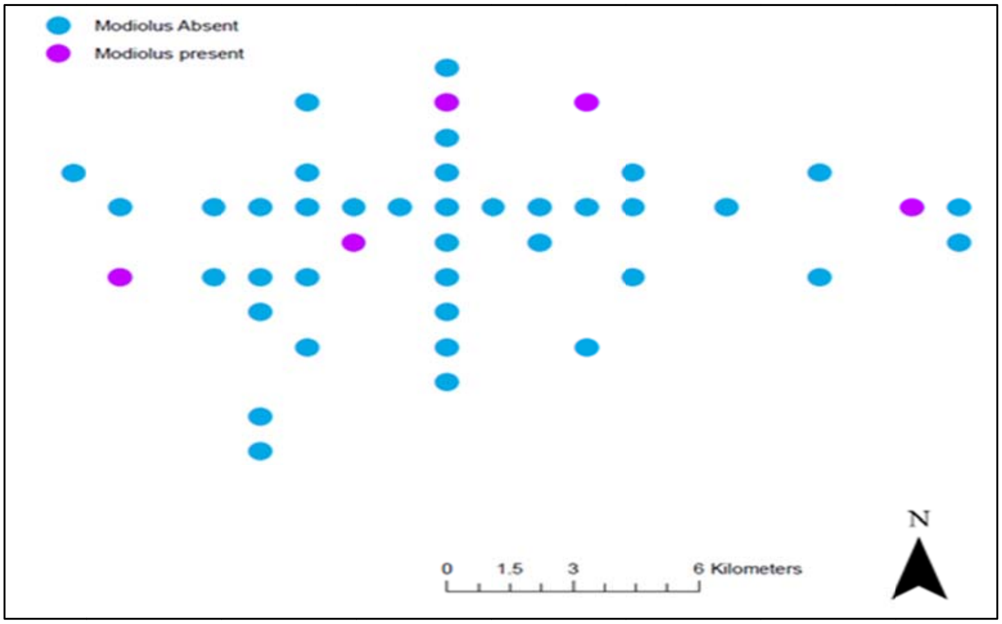


Figure E.1: Typical survey transect illustrating the presence and absence of *Modiolus modiolus* specimens

Source: (Flanders Marine Institute, 2004); *Dataset: "Marine benthic dataset (version 1) commissioned by UKOOA"*

The data obtained directly from the data managers at VLIZ required minimal formatting upon receipt. The data was provided in excel format and listed every survey station contained within the above datasets and which stations *M. modiolus* were recorded at. In order for the data to be input into ArcMAP, it was necessary to insert a binary code into the spreadsheet in order for ArcGIS to distinguish between presence and absence sites. This code was simply: *Modiolus* Present and *Modiolus* Absent. No further data formatting was required.

Table E.1: EurOBIS Database Surveys

Survey/Dataset Name	*Modiolus modiolus* Present?
Rockall survey ICES Vib	No
North Sea international bottom trawl survey	No
Marine Life Information Network (MarLIN) marine survey data (Professional)	**Yes**
Marine Nature Conservation Review (MNCR) and associated benthic marine data held and managed by English Nature	**Yes**
Marine benthic dataset (version 1) commissioned by UKOOA	**Yes**
Scottish Western Coast Via groundfish survey	No
Marine Nature Conservation Review (MNCR) and associated benthic marine data held and managed by CCW	**Yes**
Macrobenthos samples collected in the Scottish waters in 2001	No
Northern Ireland survey	No
Pembrokeshire Marine Species Atlas	**Yes**
BioMar - Ireland: benthic marine species survey	**Yes**
Long term trends in the macrobenthos of the Belgian Continental Shelf	**Yes**
Offshore ref. stations, Norwegian/Barents Sea	No
A comparison of benthic biodiversity in the North Sea, English Channel and Celtic Seas	**Yes**
Offshore ref. stations, North/Norwegian sea	No
Beam trawl surveys	No
Marine Nature Conservation Review (MNCR) and associated benthic marine data held and managed by JNCC	**Yes**
Marine Nature Conservation Review (MNCR) and associated benthic marine data held and managed by Scottish Natural Heritage	**Yes**
Macrobenthos from the Norwegian waters	No
Irish ground fish survey	No
French Southern Atlantic bottom trawl survey	No
North Sea Benthos Survey	**Yes**
National Institute of Marine Sciences and Technologies - Trawling surveys	No
National Marine Monitoring Programme data set	No
Baltic international trawl surveys	No

Source: (Flanders Marine Institute, 2004)

Figures E.2 to E.10 illustrate the presence and absence of *M. modiolus* specimens collated from the survey data outlined in Table E.2.

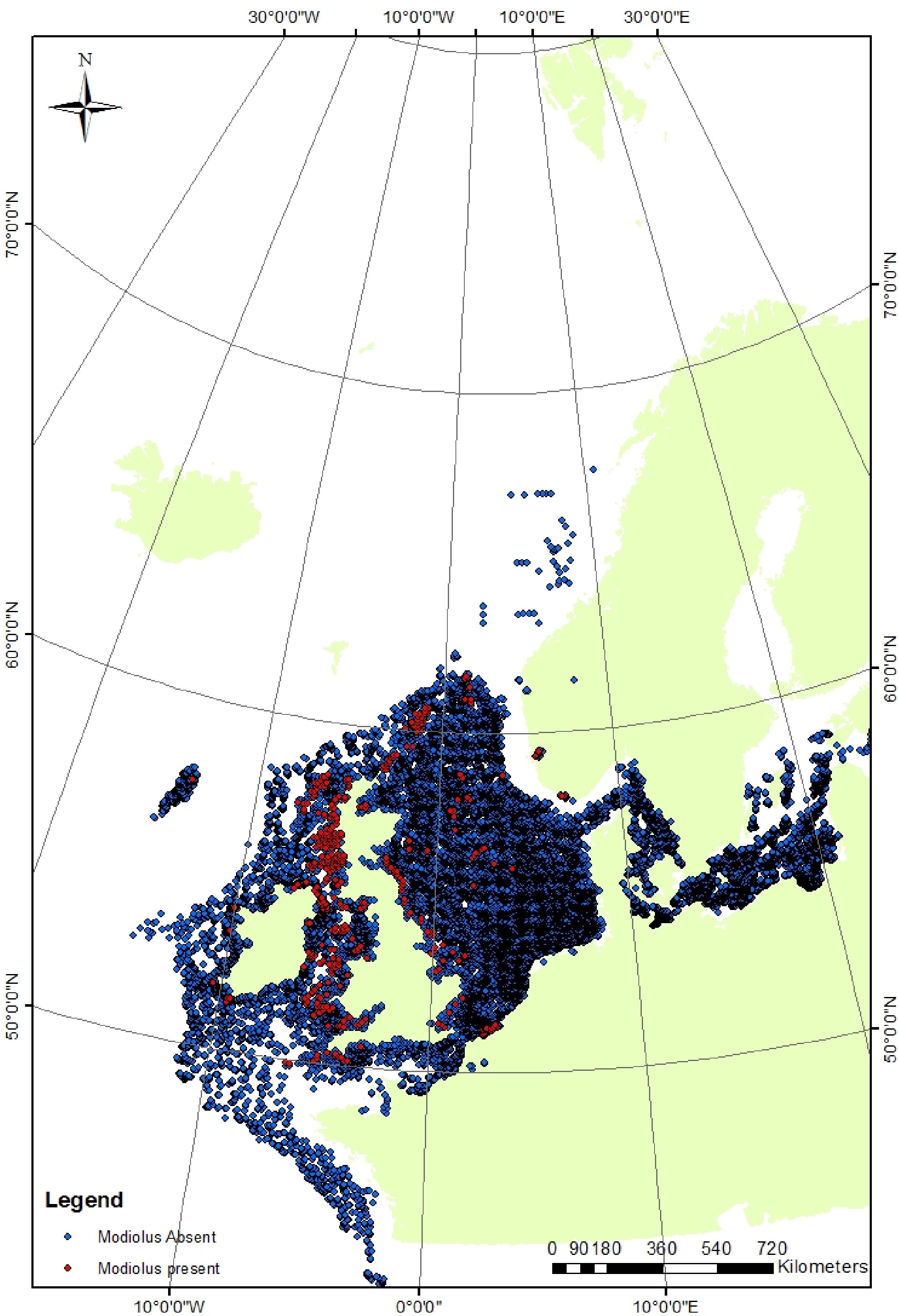


Figure E.8.1: ***Modiolus modiolus*** **presence and absence distribution**

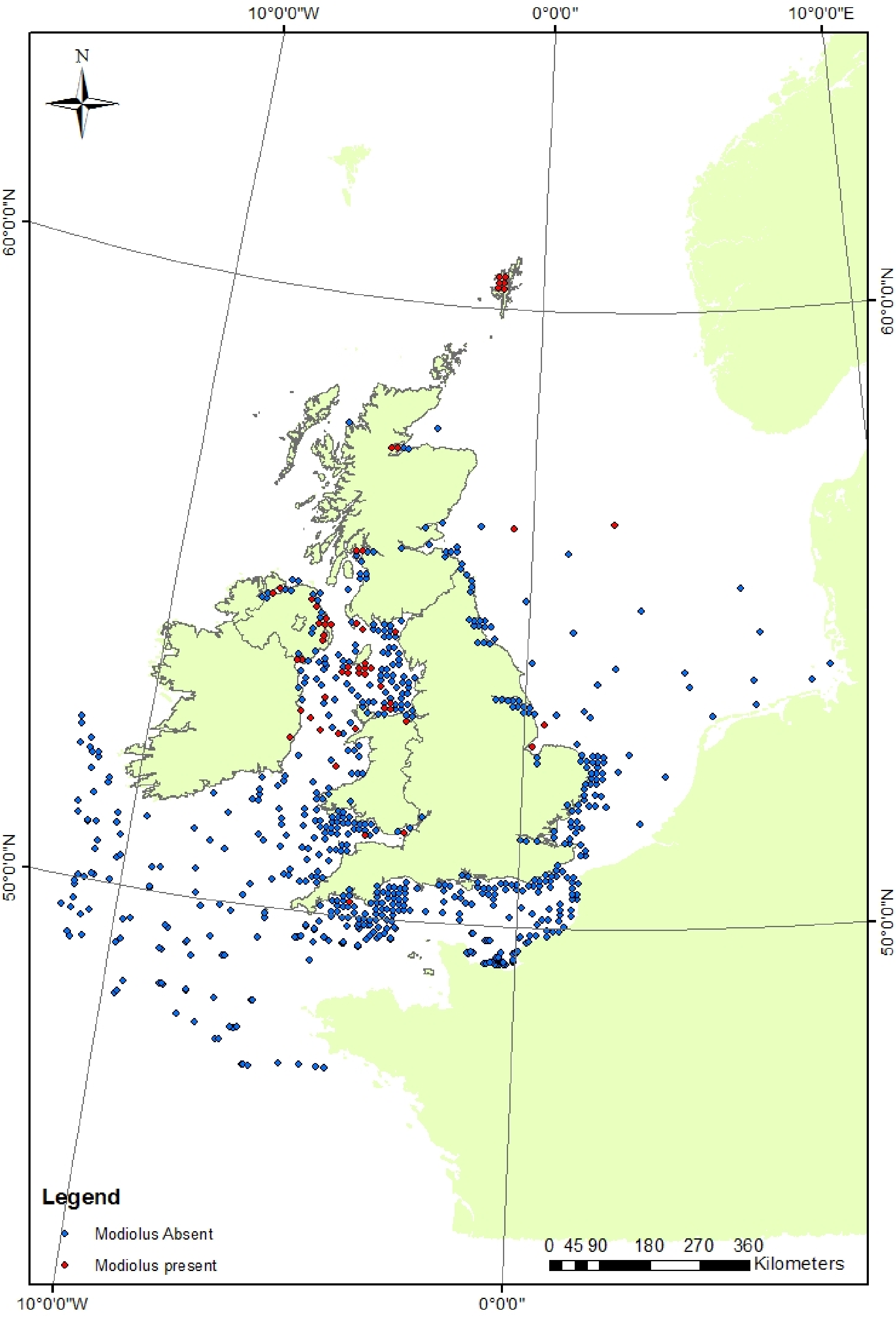


Figure E.8.2: Marine Life Information Network (MarLIN) marine survey data (Professional)

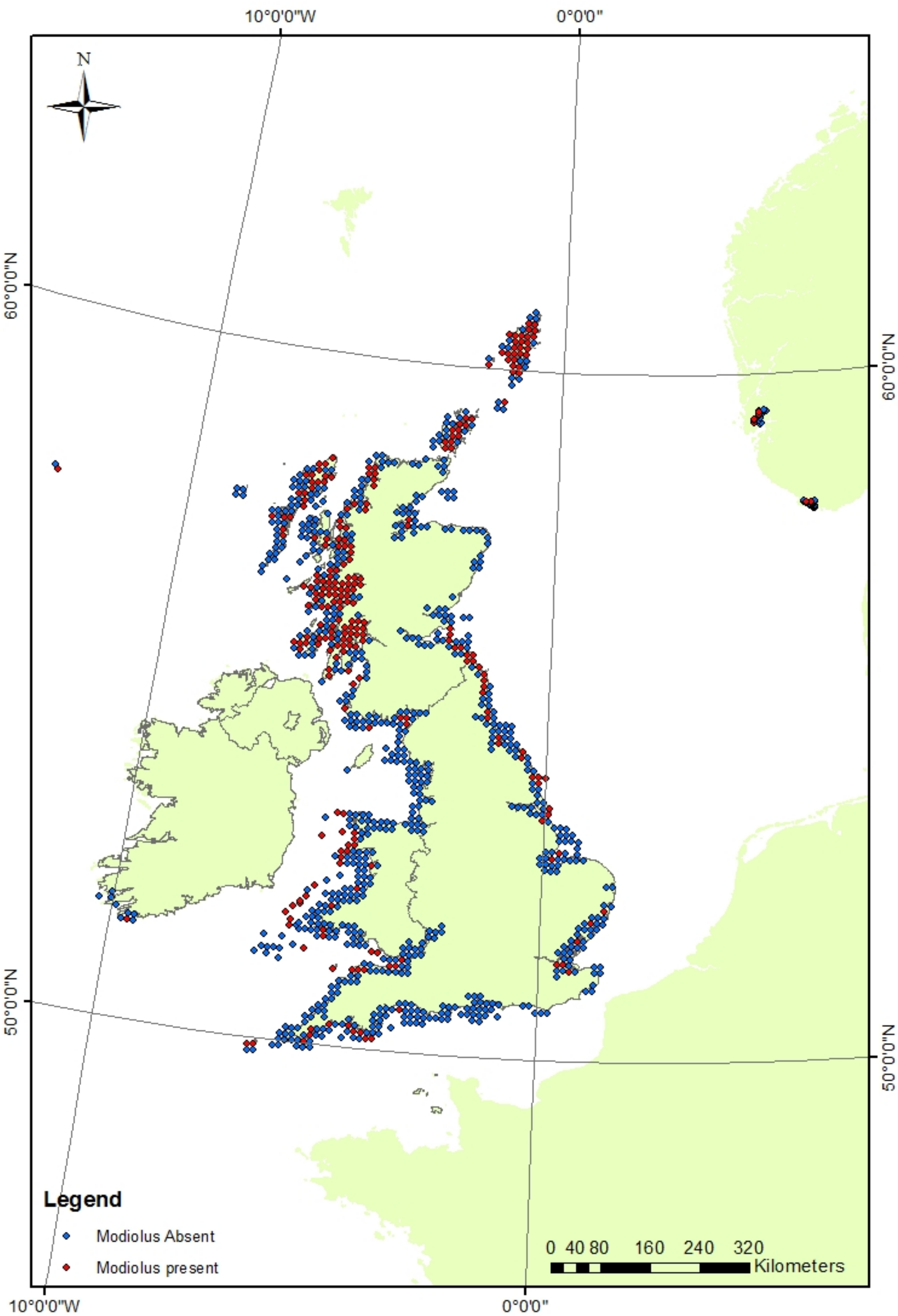


Figure E.8.3: Marine Nature Conservation Review (MNCR) and associated benthic marine data held and managed by English Nature, Countryside Council for Wales, the Joint Nature Conservation Committee and Scottish Natural Heritage Presence and Absence Data

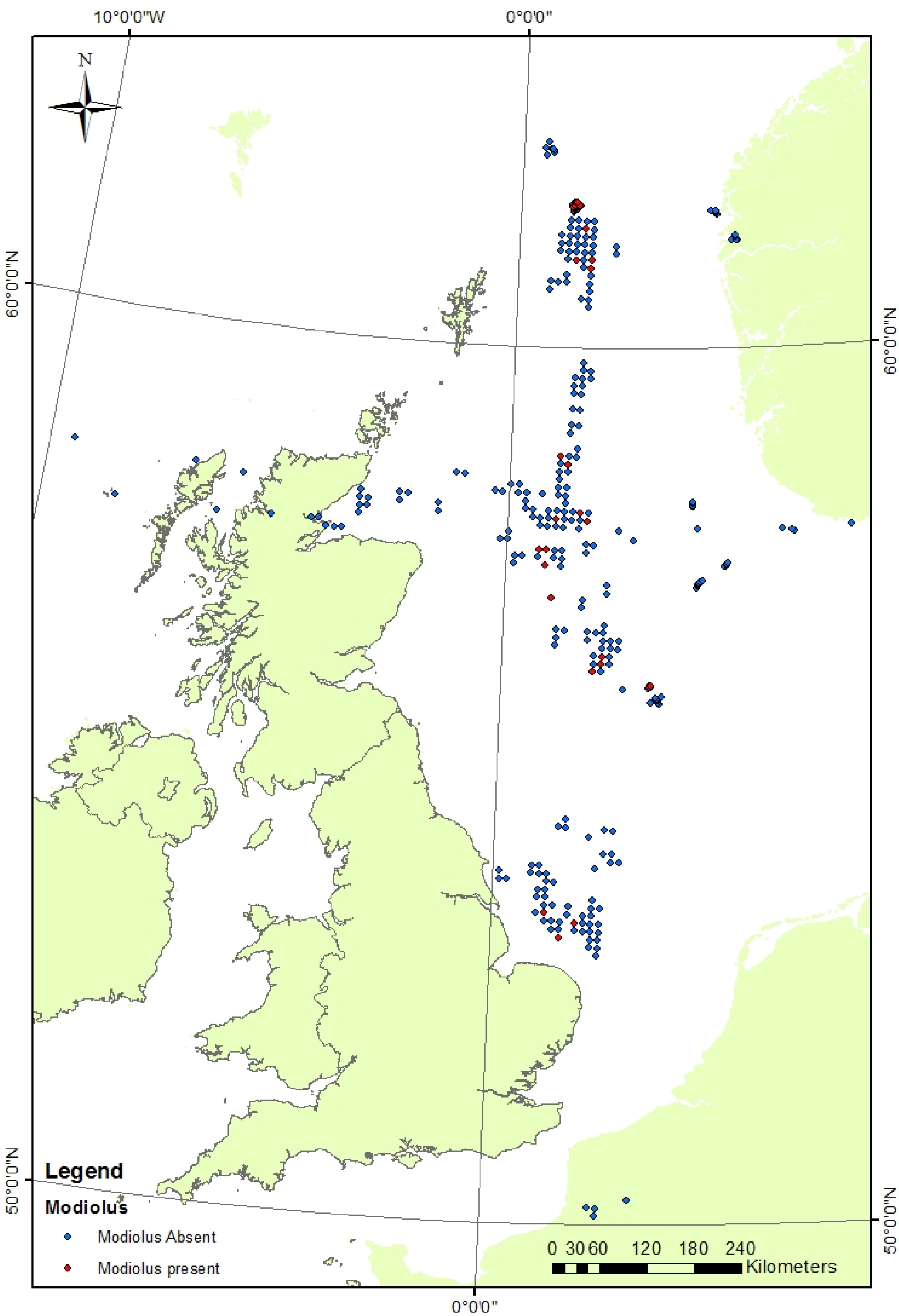


Figure E.8.4: Marine benthic dataset (version 1) commissioned by UKOOA Presence and Absence Data

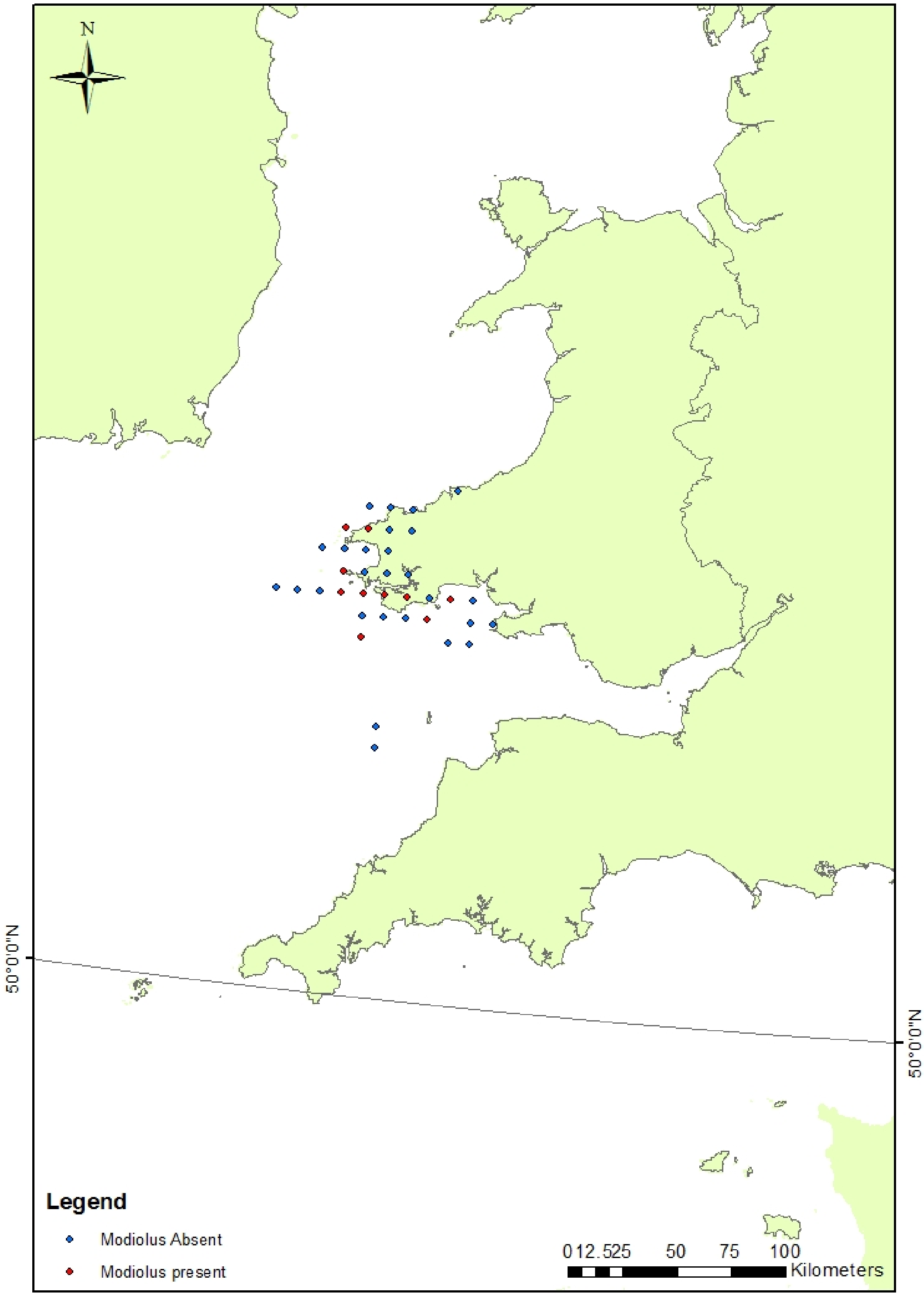


Figure E.8.5: Pembrokeshire Marine Species Atlas Presence and Absence Data

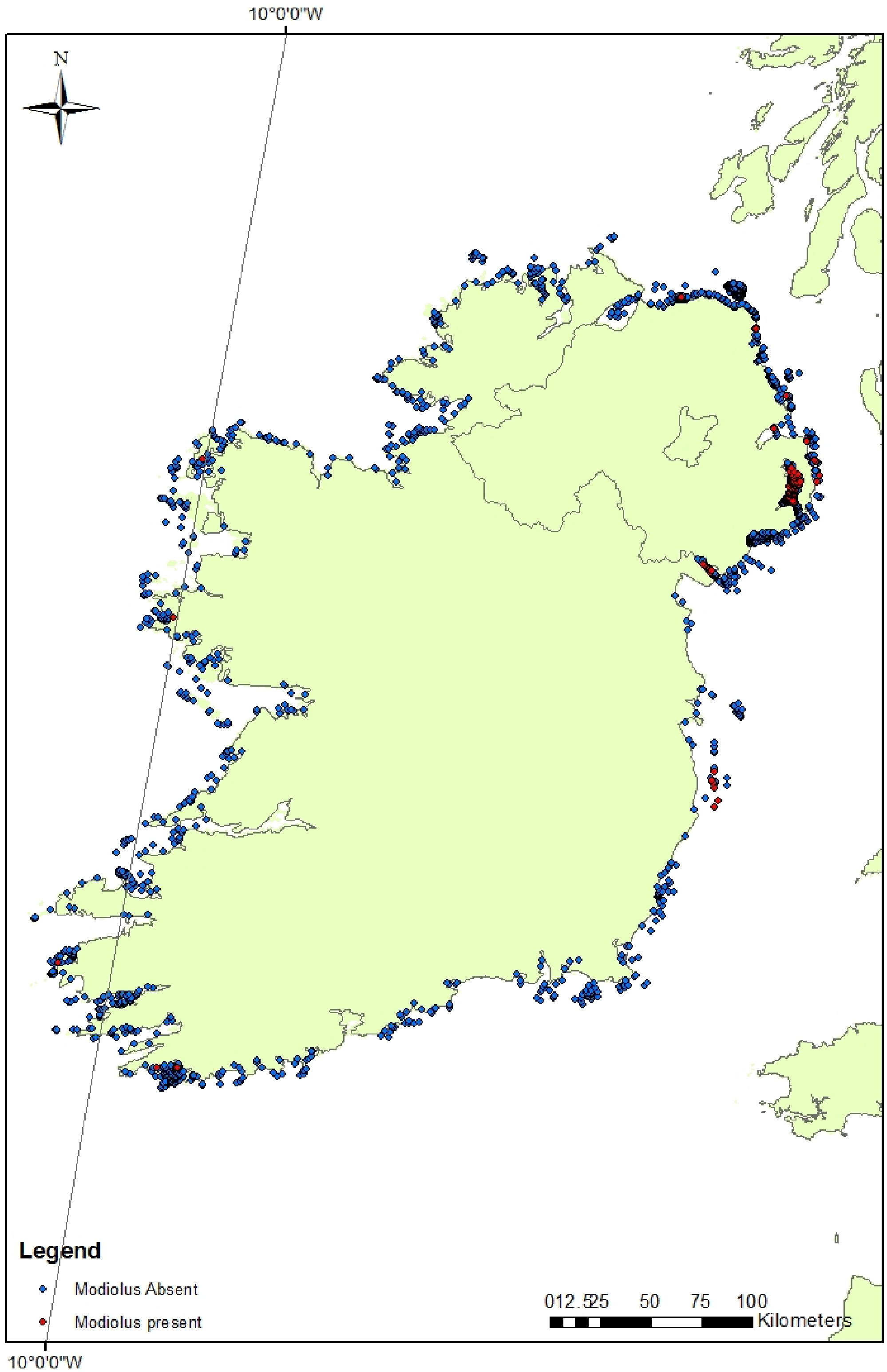


Figure E.8.6: BioMar - Ireland: benthic marine species survey Presence and Absence Data

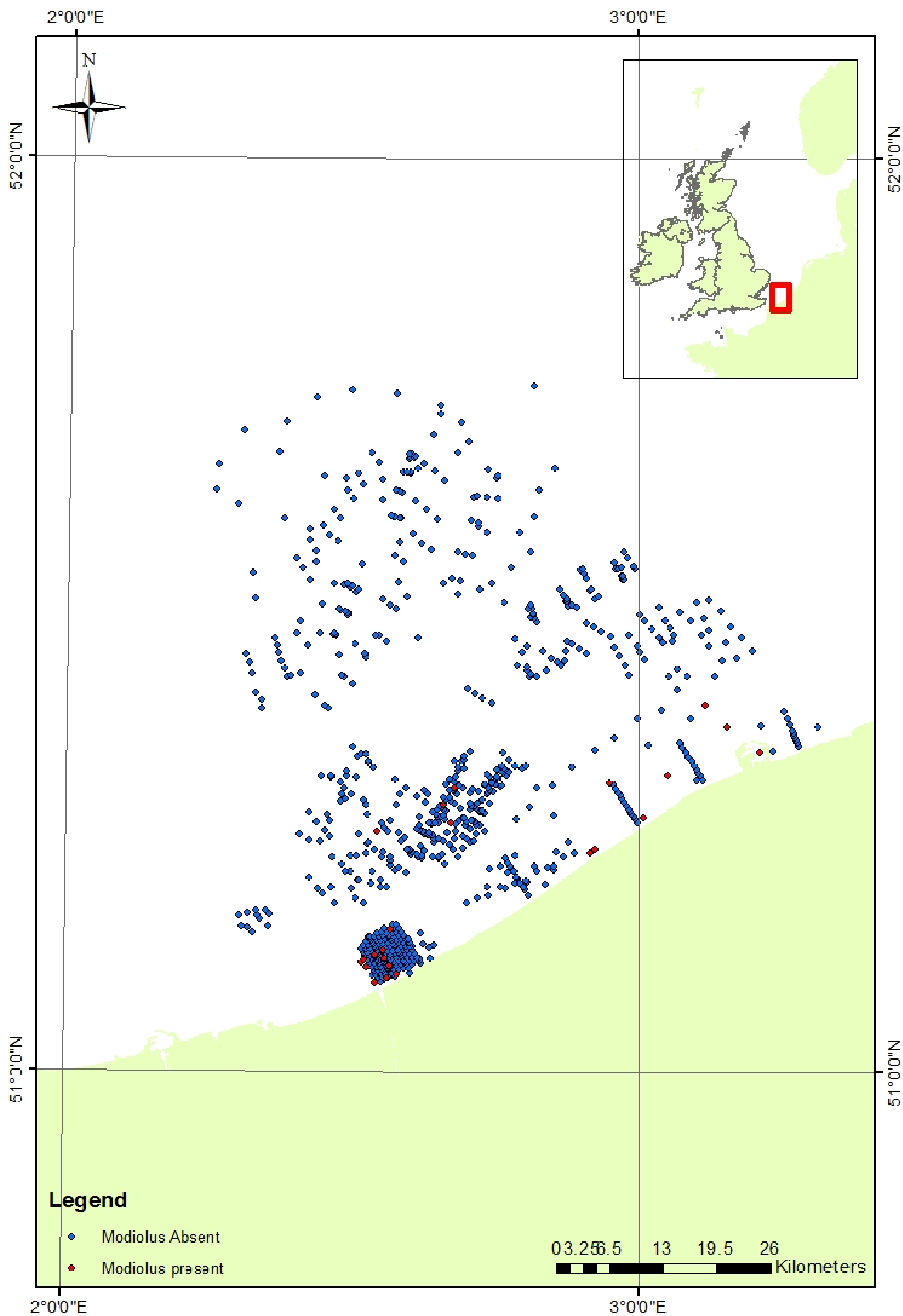


Figure E.8.7: Long term trends in the macrobenthos of the Belgian Continental Shelf Presence and Absence Data

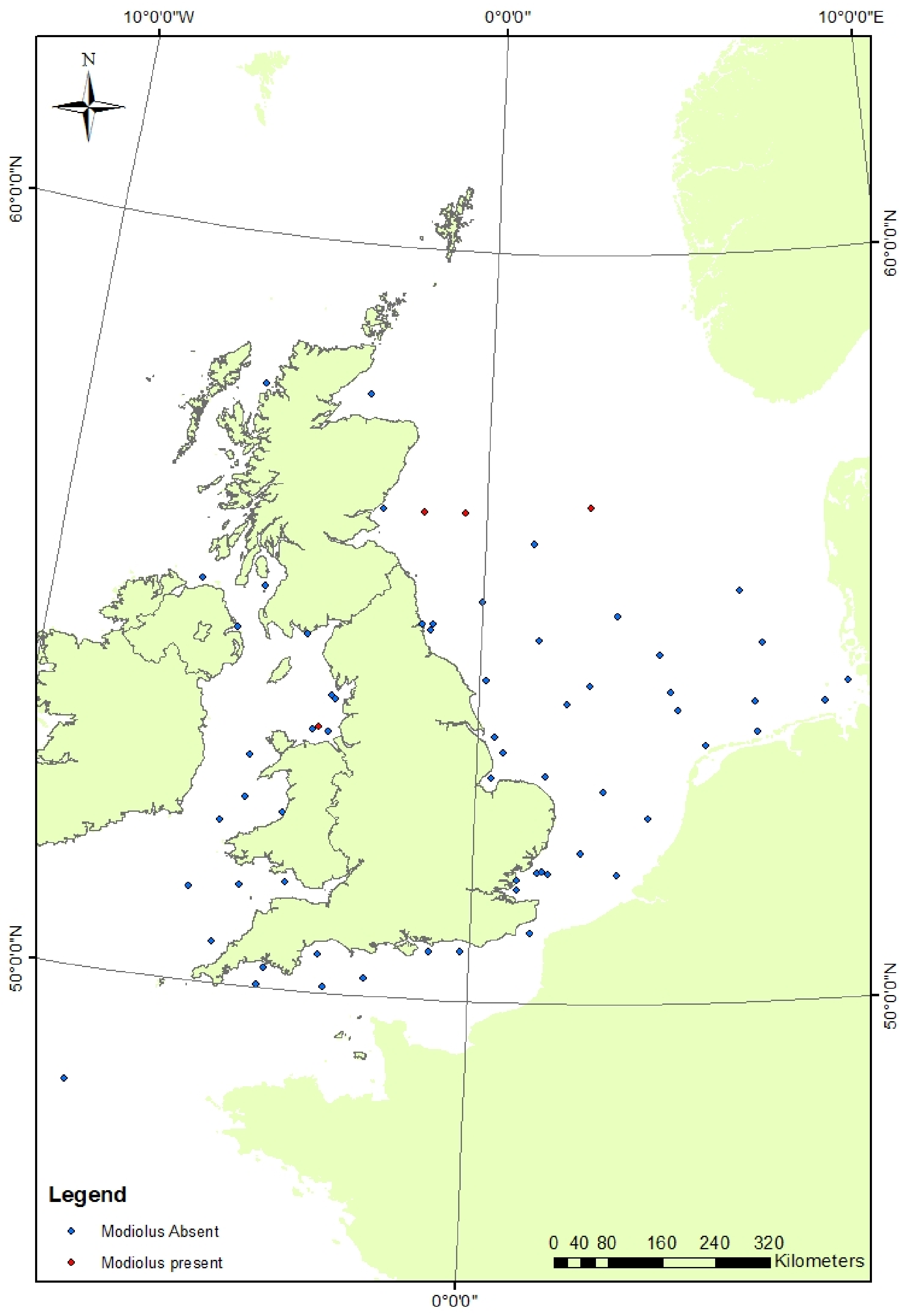


Figure E.8.8: A comparison of benthic biodiversity in the North Sea, English Channel and Celtic Seas Presence and Absence Data

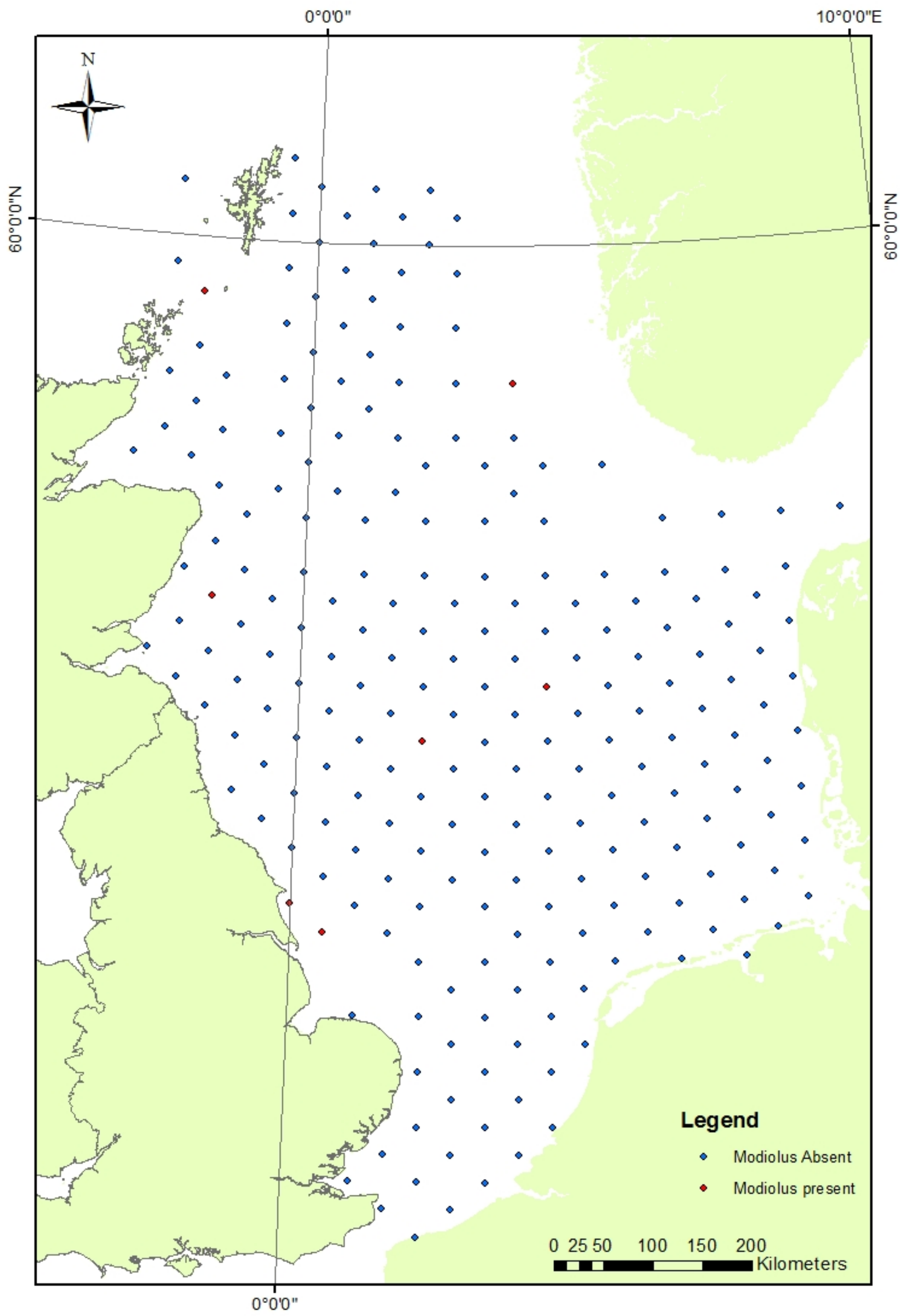


Figure E.8.9: North Sea Benthos Survey Presence and Absence Data

Appendix F. Primer Testing and Design

Plate No.	Well No.	PCR Product	Contig Assembled	Microsatellite	Primers designed	Forward Primer	Reverse Primer	Primer Name
S1	1	Yes	Yes (poor quality)	No	n/a	n/a	n/a	n/a
S1	2	Yes	Yes (poor quality)	No	n/a	n/a	n/a	n/a
S1	3	Yes	Yes (poor quality)	No	n/a	n/a	n/a	n/a
S1	4	Yes	Yes (poor quality)	AC	ERROR	n/a	n/a	n/a
S1	5	Yes	Yes	No	n/a	n/a	n/a	n/a
S1	6	Yes	Yes	GAA	Yes	AAGGTCAAGGTC ACATTGAAGGT	TAGAGCTTA TGGCTGCGTTGT	Modimicro 5
S1	7	Yes	Yes (poor quality)	No	n/a	n/a	n/a	n/a
S1	8	Yes	Yes	GT	ERROR	n/a	n/a	n/a
S1	9	Yes	Yes	No	n/a	n/a	n/a	n/a
S1	10	No	No	n/a	n/a	n/a	n/a	n/a
S1	11	Yes	Yes	GT	ERROR	n/a	n/a	n/a
S1	12	Yes	Yes	No	n/a	n/a	n/a	n/a
S1	13	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	14	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	15	Yes	Yes	GA	ERROR	n/a	n/a	n/a
S1	16	Yes	Yes	CA	ERROR	n/a	n/a	n/a
S1	17	Yes	Yes	CT	ERROR	n/a	n/a	n/a
S1	18	Yes	Yes	GA	Yes	CACTGTATTTC AAGATGTCGCC	TCACAAGTGTA TAGAACCCCTCA	Modimicro 4
S1	19	Yes	Yes	GT	ERROR	n/a	n/a	n/a
S1	20	Yes	Yes	CAT	ERROR	n/a	n/a	n/a
S1	21	Yes	Yes	GTT	ERROR	n/a	n/a	n/a
S1	22	Yes	Yes	GT	ERROR	n/a	n/a	n/a
S1	23	No	No	n/a	n/a	n/a	n/a	n/a
S1	24	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	25	No	No	n/a	n/a	n/a	n/a	n/a
S1	26	No	No	n/a	n/a	n/a	n/a	n/a
S1	27	No	No	n/a	n/a	n/a	n/a	n/a
S1	28	No	No	n/a	n/a	n/a	n/a	n/a
S1	29	No	No	n/a	n/a	n/a	n/a	n/a
S1	30	No	No	n/a	n/a	n/a	n/a	n/a
S1	31	Yes	No	n/a	n/a	n/a	n/a	n/a

Plate No.	Well No.	PCR Product	Contig Assembled	Microsatellite	Primers designed	Forward Primer	Reverse Primer	Primer Name
S1	32	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	33	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	34	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	35	No	No	n/a	n/a	n/a	n/a	n/a
S1	36	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	37	Yes	Yes	No	n/a	n/a	n/a	n/a
S1	38	No	No	n/a	n/a	n/a	n/a	n/a
S1	39	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	40	No	No	n/a	n/a	n/a	n/a	n/a
S1	41	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	42	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	43	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	44	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	45	Yes	Yes	No	n/a	n/a	n/a	n/a
S1	46	No	No	n/a	n/a	n/a	n/a	n/a
S1	47	No	No	n/a	n/a	n/a	n/a	n/a
S1	48	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	49	No	No	n/a	n/a	n/a	n/a	n/a
S1	50	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	51	No	No	n/a	n/a	n/a	n/a	n/a
S1	52	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	53	Yes	Yes	No	n/a	n/a	n/a	n/a
S1	54	No	No	n/a	n/a	n/a	n/a	n/a
S1	55	Yes	Yes	No	n/a	n/a	n/a	n/a
S1	56	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	57	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	58	No	n/a	n/a	n/a	n/a	n/a	n/a
S1	59	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	60	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	61	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	62	Yes	Yes	No	n/a	n/a	n/a	n/a
S1	63	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	64	Yes	Yes	No	n/a	n/a	n/a	n/a
S1	65	Yes	Yes	No	n/a	n/a	n/a	n/a
S1	66	Yes	No	n/a	n/a	n/a	n/a	n/a

Plate No.	Well No.	PCR Product	Contig Assembled	Microsatellite	Primers designed	Forward Primer	Reverse Primer	Primer Name
S1	67	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	68	Yes	Yes	No	n/a	n/a	n/a	n/a
S1	69	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	70	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	71	Yes	Yes	AGAC(6)	Yes	CAATCAATCACACAACCAGACAG A	TGGCACGAGCGTTAGCAG	ModiMicro 6
S1	72	Yes	Yes	No	n/a	n/a	n/a	n/a
S1	73	Yes	Yes	GT(8)	ERROR	n/a	n/a	n/a
S1	74	Yes	Yes	No	n/a	n/a	n/a	n/a
S1	75	Yes	Yes	No	n/a	n/a	n/a	n/a
S1	76	Yes	Yes	No	n/a	n/a	n/a	n/a
S1	77	Yes	Yes	TG(11)	Yes	TAGCAGAATCCAGCCCAAAA	CGATTGACGGAAAGTTACGCT	ModiMicro 7
S1	78	Yes	Yes	CA(8)	Yes	GGATGGTCACTCCTCACATTTT	GCCTAGCATAGCGGAATCAAT	ModiMicro 8
S1	79	Yes	Yes	ACA(6)	Yes	ACAGCAACTGACCTCCAGATTT	TTCTTCTTTTCCTTATCCGGTG	ModiMicro 9
S1	80	Yes	Yes	AC(14)	Yes	GCACACACACTATCTAAACAACCC	TGAGAGAGAGAGAAAGAGAGAGGA A	n/a
S1	80	Yes	Yes	TC	ERROR	n/a	n/a	n/a
S1	81	Yes	Yes	No	n/a	n/a	n/a	n/a
S1	82	Yes	Yes	No	n/a	n/a	n/a	n/a
S1	83	Yes	Yes	No	n/a	n/a	n/a	n/a
S1	84	Yes	Yes	No	n/a	n/a	n/a	n/a
S1	85	Yes	Yes	GAT(7)	Yes	ACATAGCGCGGCAAGTTC	TTGATCTCATTTCGTGGTTGAG	ModiMicro 10
S1	86	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	87	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	88	Yes	Yes	No	n/a	n/a	n/a	n/a
S1	89	Yes	No	n/a	n/a	n/a	n/a	n/a
S1	90	Yes	Yes	GAA(7)	Yes	AGAATCCTTTCTGTGTTGTCCG	CATCTGCCTACCTACAGTTCCC	ModiMicro 11
S1	91	Yes	Yes	TGA(6)	Yes	GGTTCACCACCATGTATGAGC	GCAGAGTGGGCATCTACAGTTA	ModiMicro 12

Plate No.	Well No.	PCR Product	Contig Assembled	Microsatellite	Primers designed	Forward Primer	Reverse Primer	Primer Name
S1	92	Yes	Yes	TC(11)	Yes	CACAGCCTCCTGGTCACAATA	TGGCGTGTTATTCTAGCAAATG	ModiMicro 13
S1	93	Yes	Yes	No	n/a	n/a	n/a	n/a
S1	94	No	n/a	n/a	n/a	n/a	n/a	n/a
S1	95	Yes	Yes	CA(10)	Yes	CCACACTCACACACTCACACAC	TAGCAGAATCACTACGCTCCAA	ModiMicro 14
S1	96	Yes	Yes	TG(12)	ERROR			
S2	1	Yes	No	n/a	n/a	n/a	n/a	n/a
S2	2	Yes	Yes	CA(7)	Yes	CCATGTGAGATTGATCCTTGAG	CCACGCACCTAATGGTTATAGA	ModiMicro 15
S2	3	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	4	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	5	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	6	Yes	Yes	AC	ERROR	n/a	n/a	n/a
S2	7	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	8	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	9	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	10	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	11	Yes	Yes	TCT(8)	Yes	TTCAGAGTAGATTTAGGGTGTGAG G	CTAGCAGAATCACGACACATGC	ModiMicro 16
S2	12	Yes	No	n/a	n/a	n/a	n/a	n/a
S2	13	Yes	Yes	TGA	ERROR	n/a	n/a	n/a
S2	14	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	15	Yes	Yes	AGA(7)	Yes	CGTCCAGTGAGCAGTATTTCAG	CATGCAGGATAAAGATCCCTTC	ModiMicro 17
S2	16	Yes	No	n/a	n/a	n/a	n/a	n/a
S2	17	Yes	Yes	No	n/a	n/a	n/a	n/a
S2	18	Yes	Yes	TCA(10)	Yes	CTAGCAGAATCCTCGTCCAGAG	GTTCAAGATCAGCAGGACCAAG	ModiMicro 18
S2	19	Yes	Yes	No	n/a	n/a	n/a	n/a
S2	20	Yes	Yes	CA(11)	Yes	TAGCAGAATCCATCCTTCAACA	ACATTGCATATAAACGGGAGGT	ModiMicro 19
S2	21	No	n/a	n/a	n/a	n/a	n/a	n/a
S2	22	Yes (faint)	n/a	n/a	n/a	n/a	n/a	n/a
S2	23	Yes	n/a	n/a	n/a	n/a	n/a	n/a

Plate No.	Well No.	PCR Product	Contig Assembled	Microsatellite	Primers designed	Forward Primer	Reverse Primer	Primer Name
S2	24	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	25	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	26	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	27	Yes	Yes	TCA(10)	Yes	AATTGCTCACTTGGCGTAAAAC	TGGAAATGGAGAGACAGATCCT	ModiMicro 20
S2	28	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	29	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	30	Yes	Yes	GAA	Yes	GCATTCAAATCTCAAGTGACCA	GAAAAGCGTA GCAGAATCCAAT	Modimicro 3
S2	30	Yes	Yes	CAT(7)	Yes	ACACGACTGGTCATCCATACAG	AAATCCGTGCAGAATGTCAA	
S2	31	Yes	Yes	CA(9)	Yes	CATAAAAGTGTGCCCTTGATCC	AAGCGTTGTCCCATTGATATGT	ModiMicro 22
S2	32	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	33	Yes (contam?)	n/a	n/a	n/a	n/a	n/a	n/a
S2	34	Yes (contam?)	n/a	n/a	n/a	n/a	n/a	n/a
S2	35	Yes (contam?)	n/a	n/a	n/a	n/a	n/a	n/a
S2	36	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	37	Yes	Yes (poor quality)	TG	ERROR	n/a	n/a	n/a
S2	38	Yes	No	n/a	n/a	n/a	n/a	n/a
S2	39	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	40	Yes	Yes	TC	ERROR	n/a	n/a	n/a
S2	41	Yes	Yes	TTG(9)	Yes	CTATTCTGACGACTGACGATGG	CTTATGCCCTTCAACAACAACA	ModiMicro 23
S2	42	Yes	Yes	CT(23)	Yes	ACTAAAACTGACCGCCACGATA	GATTTTCTTCGGATTTGAGGTG	ModiMicro 24
S2	43	Yes	Yes	CA(9)	Yes	CATAAAAGTGTGCCCTTGATCC	AAGCGTTGTCCCATTGATATGT	ModiMicro 25
S2	44	Yes (contam?)	n/a	n/a	n/a	n/a	n/a	n/a
S2	45	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	46	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	47	Yes (contam?)	n/a	n/a	n/a	n/a	n/a	n/a
S2	48	Yes	n/a	n/a	n/a	n/a	n/a	n/a

Plate No.	Well No.	PCR Product	Contig Assembled	Microsatellite	Primers designed	Forward Primer	Reverse Primer	Primer Name
S2	49	Yes	Yes	TCT(8)	Yes	TTCAGAGTAGATTTAGGGTGTGAG G	CTAGCAGAATCACGACACATGC	ModiMicro 26
S2	50	No	No	n/a	n/a	n/a	n/a	n/a
S2	51	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	52	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	53	Yes	Yes	CA	Yes	CTCCGCTATGTT TGACCATGTA	TCCACACCGAGTAACAAATCAG	Modimicro 2
S2	54	Yes	Yes	TG	Yes	AAGCGTTGTCCCATTGATATGT	CATAAAAGTGTGCCCTTGATCC	Modimicro 1
S2	55	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	56	Yes	Yes	CA	ERROR	n/a	n/a	n/a
S2	57	No	n/a	n/a	n/a	n/a	n/a	n/a
S2	58	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	59	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	60	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	61	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	62	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	63	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	64	Yes	Yes	TTC	ERROR	n/a	n/a	n/a
S2	65	Yes	Yes	TAC(13)	Yes	GCTTTAGCGTCAACTATGGCTT	CTAGCAGAATCACATGGGTCAA	ModiMicro 27
S2	66	Yes	Yes	TG	ERROR	n/a	n/a	n/a
S2	67	Yes	Yes	CA	ERROR	n/a	n/a	n/a
S2	68	Yes	Yes	ATC	ERROR	n/a	n/a	n/a
S2	69	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	70	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	71	Yes	Yes	AAC(6)	Yes	CTATTCCACAATTCCAGCCTTC	TGCTGCTCTTGCTCAACATTAC	ModiMicro 28
S2	72	Yes	Yes	TG(10)	Yes	TAAATAATGAGCATACCGCACG	AATCACACACCACACTCACACA	ModiMicro 29
S2	73	Yes	Yes	CA(9)	Yes	CACACAAGACAGGCCAGATAGA	GAAGAATCCCCACAAACACATT	ModiMicro 30
S2	74	Yes	Yes	GT(19)	Yes	ACATGATCCATACGATGAGTGC	GCTCACCAGCTAGACCAATCTC	ModiMicro 31

Plate No.	Well No.	PCR Product	Contig Assembled	Microsatellite	Primers designed	Forward Primer	Reverse Primer	Primer Name
S2	75	Yes	Yes	TTC(7)	Yes	CGTTTATTATGTCTCCCCTTCG	CACCCACATGCGAAATATCTTA	ModiMicro 32
S2	76	Yes (contam?)	n/a	n/a	n/a	n/a	n/a	n/a
S2	77	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	78	Yes (contam?)	n/a	n/a	n/a	n/a	n/a	n/a
S2	79	Yes (faint)	n/a	n/a	n/a	n/a	n/a	n/a
S2	80	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	81	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	82	Yes	Yes	TG(8)	Yes	ATTGATTGGTGTGGGTTTATGC	TATATGACCGCTGAAAAGACGC	ModiMicro 33
S2	83	Yes (contam?)	n/a	n/a	n/a	n/a	n/a	n/a
S2	84	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	85	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	86	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	87	Yes	Yes	TAC(11)	Yes	GCTTTAGCGTCAACTATGGCTT	TCCAGGGTAACAAAGGTAAGGA	ModiMicro 34
S2	88	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	89	Yes (faint)	n/a	n/a	n/a	n/a	n/a	n/a
S2	90	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	91	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	92	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	93	No	n/a	n/a	n/a	n/a	n/a	n/a
S2	94	Yes	n/a	n/a	n/a	n/a	n/a	n/a
S2	95	No	n/a	n/a	n/a	n/a	n/a	n/a
S2	96	Yes	n/a	n/a	n/a	n/a	n/a	n/a

Appendix G. Larval Dispersal Figures

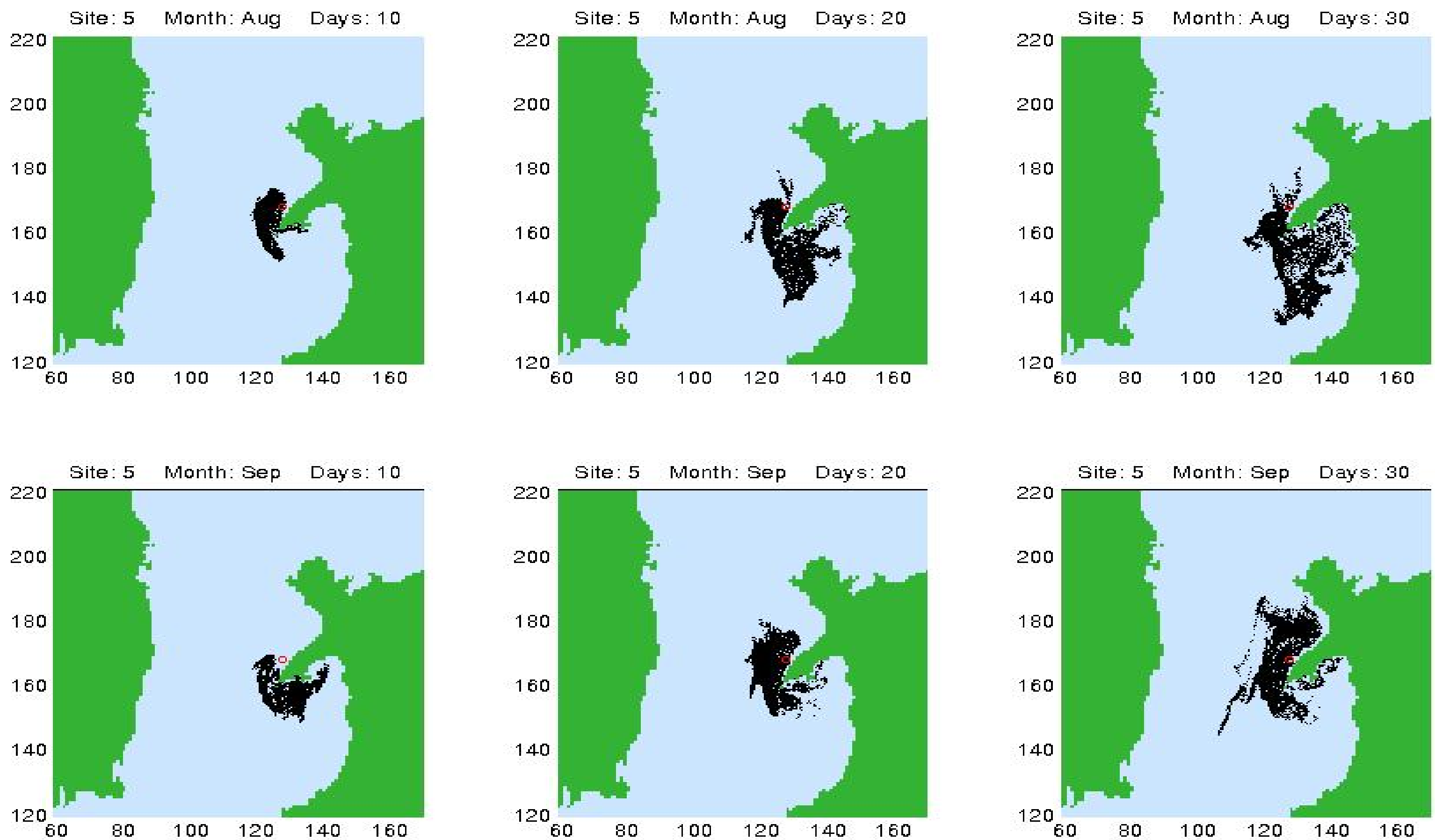
Site 1 = Ards Peninsula i

Site 2 = Ards Peninsula ii

Site 3 = Strangford Lough

Site 4 = North Llyn i

Site 5 = North Llyn ii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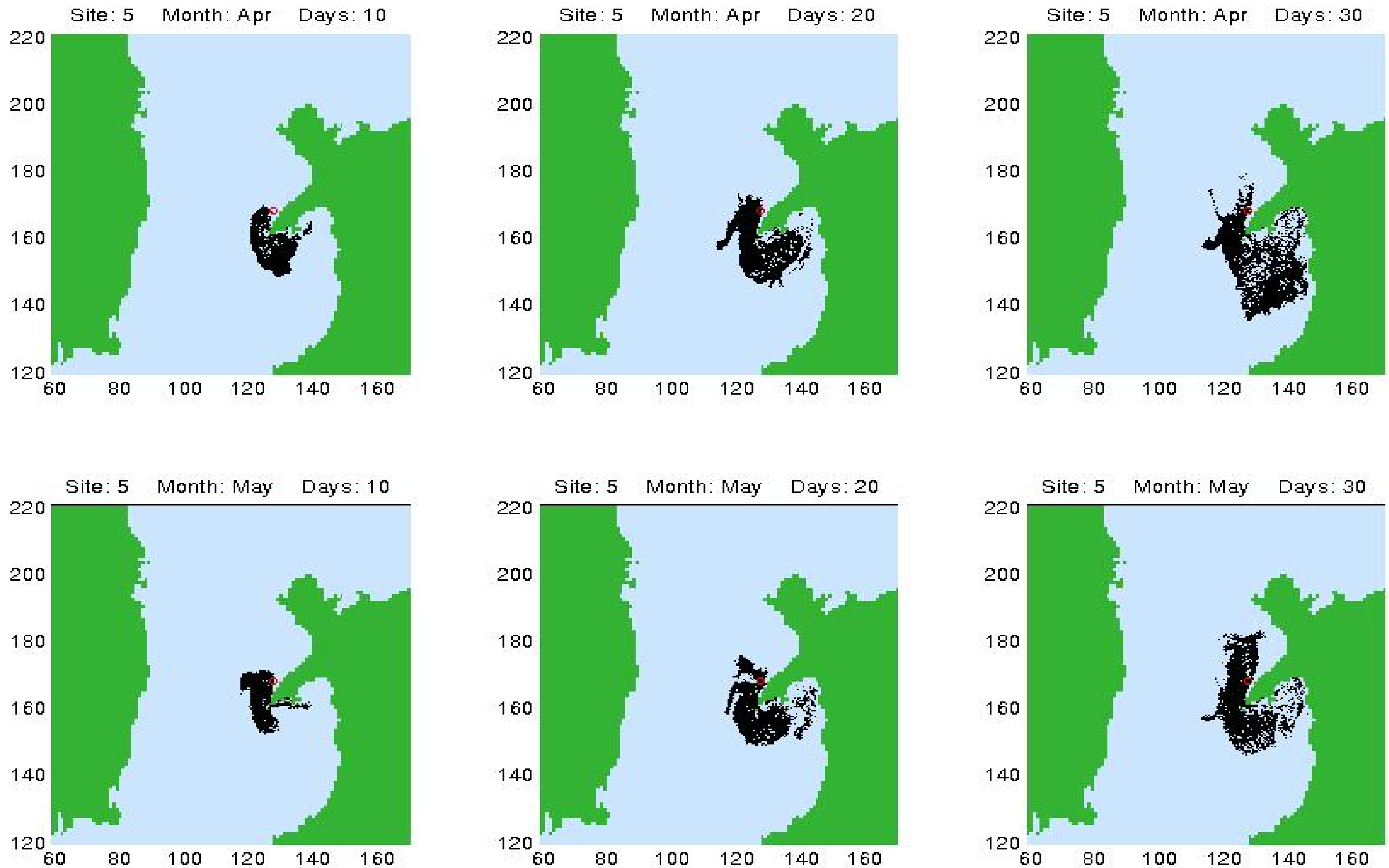
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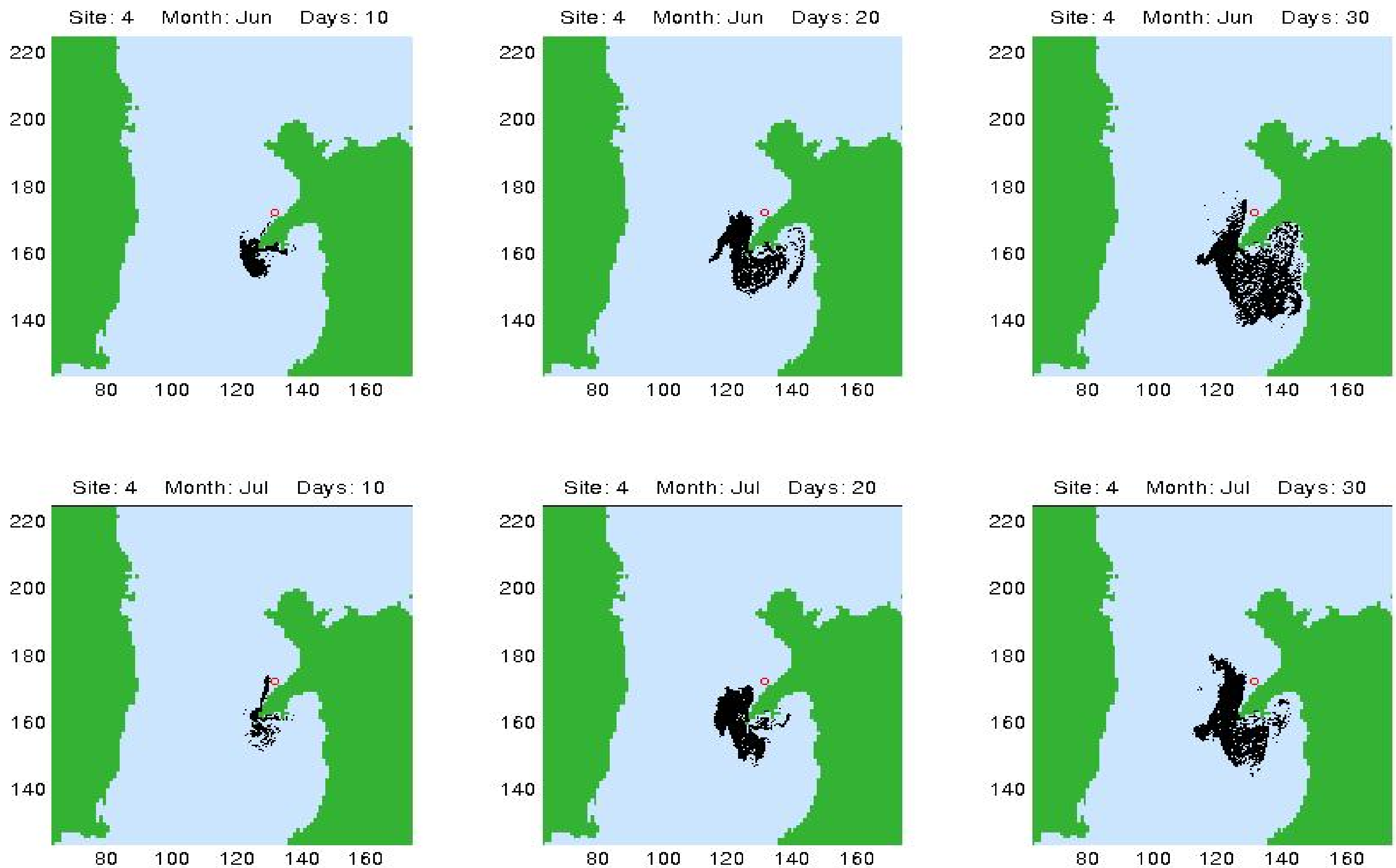
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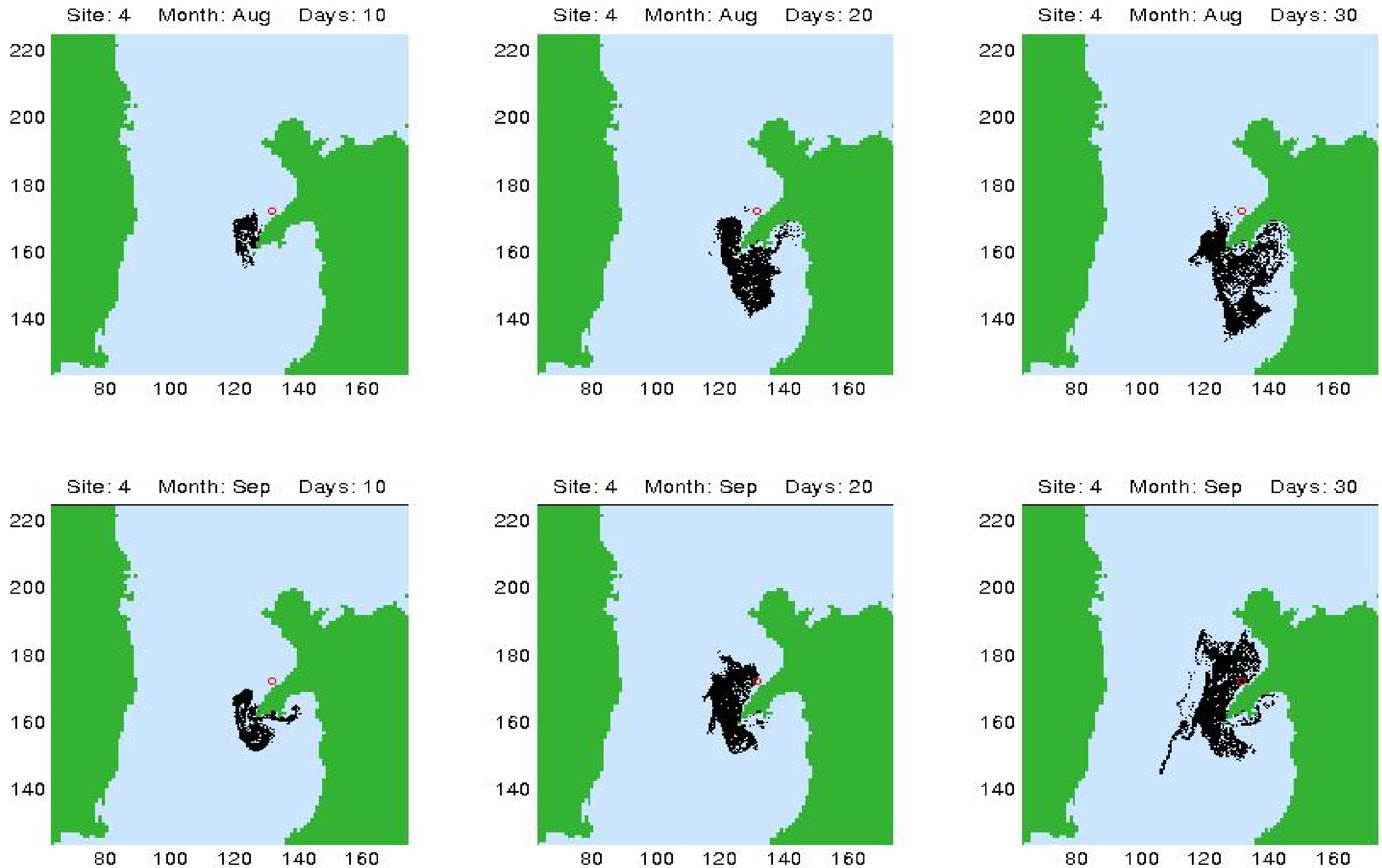
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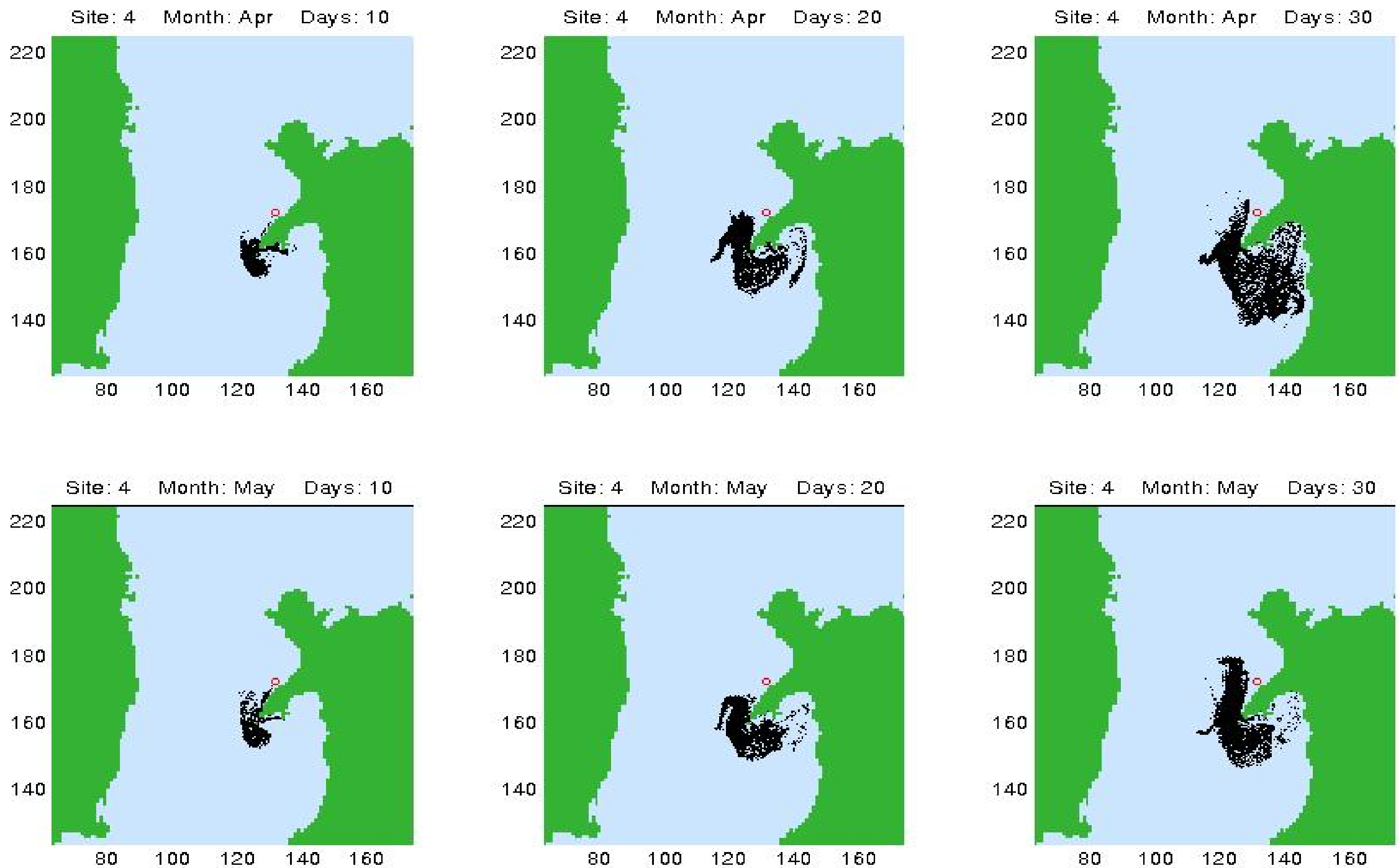
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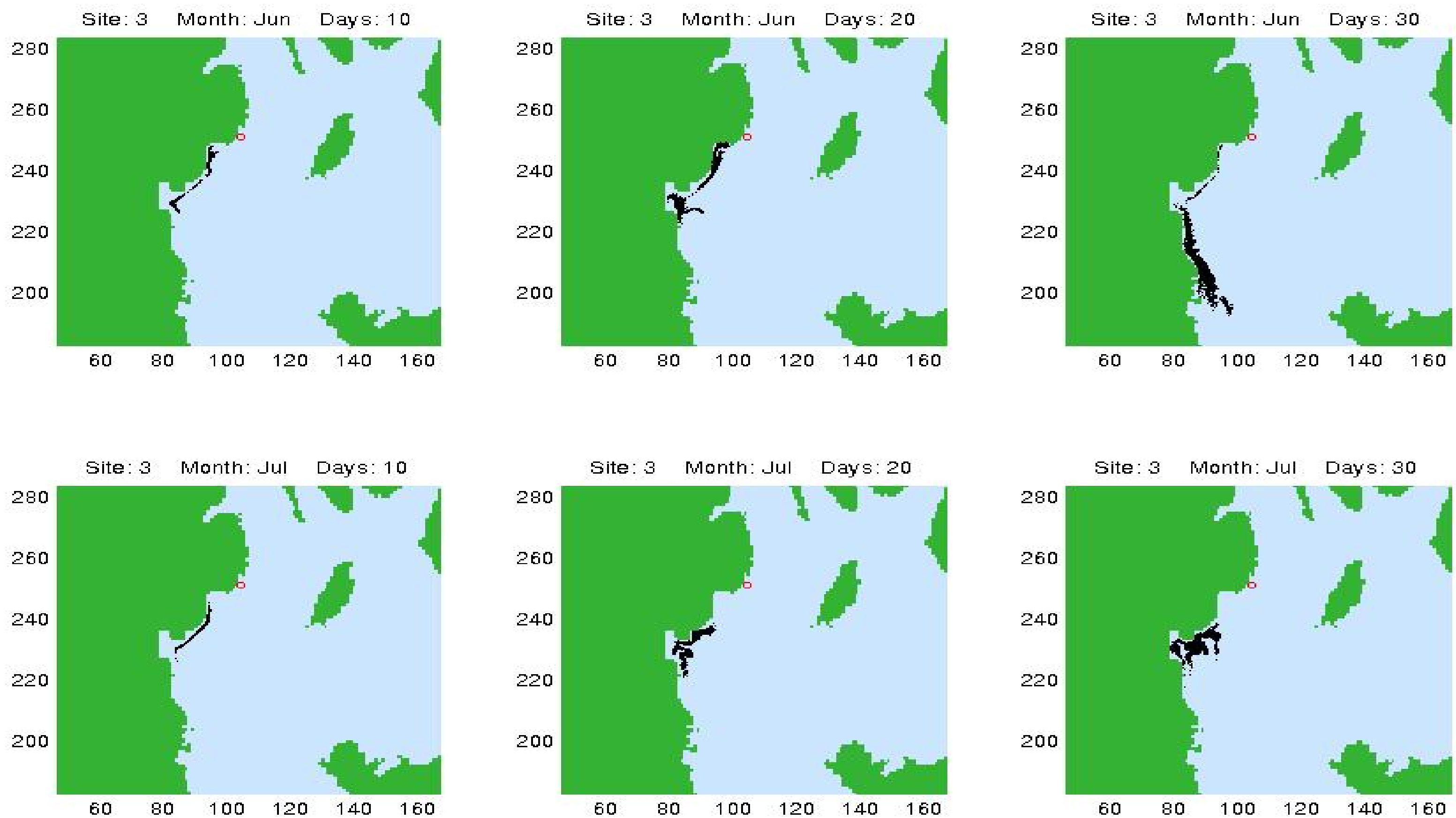
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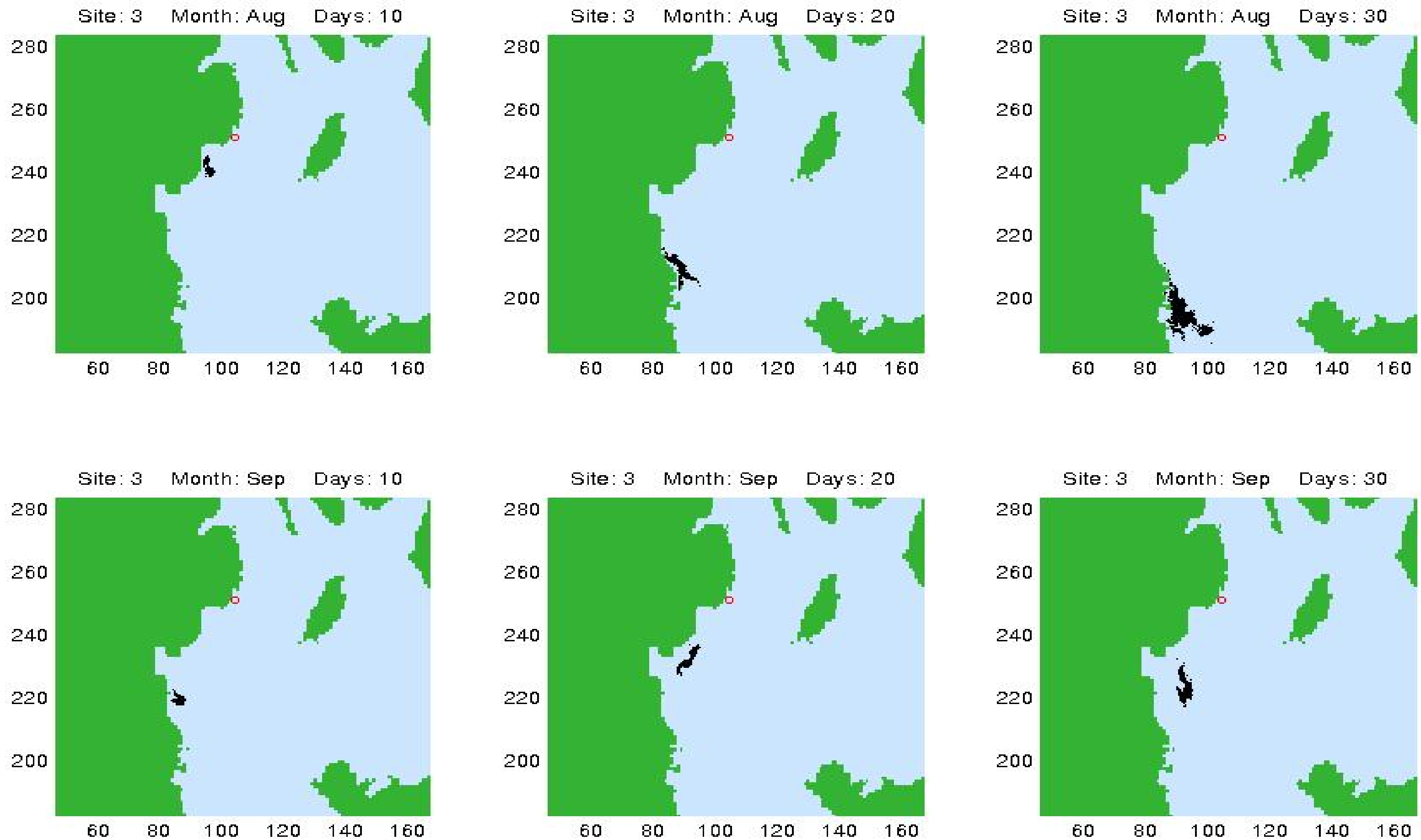
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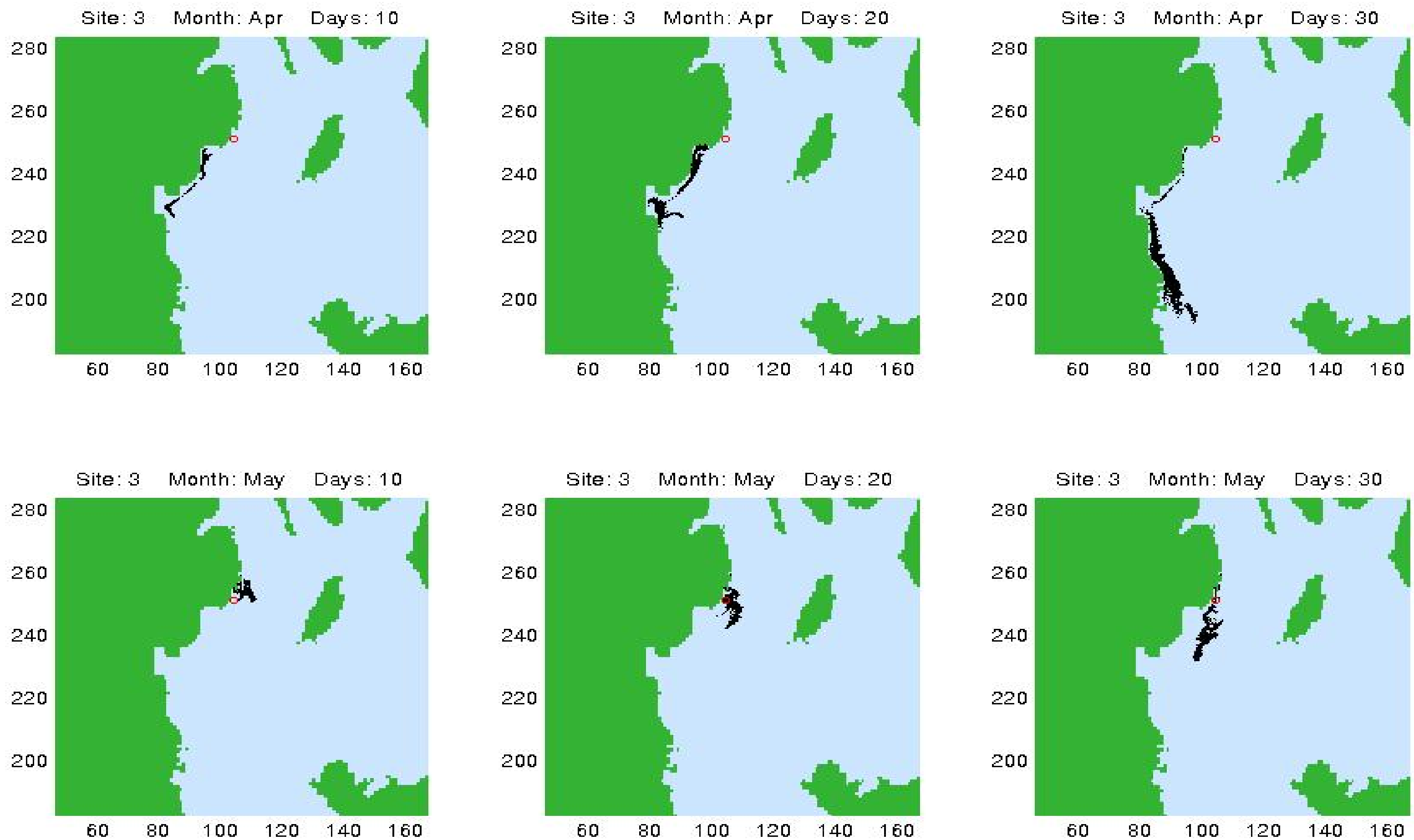
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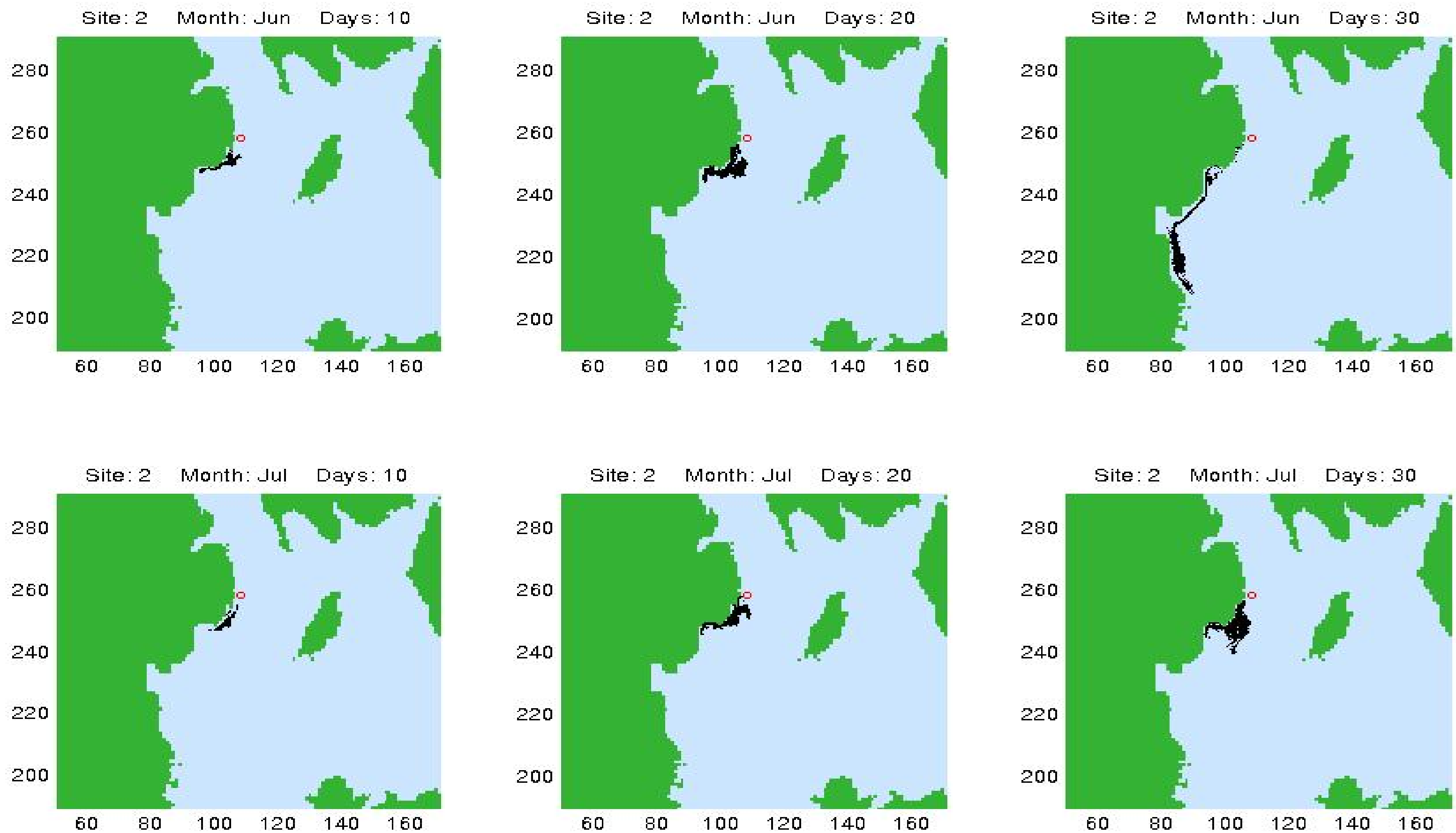
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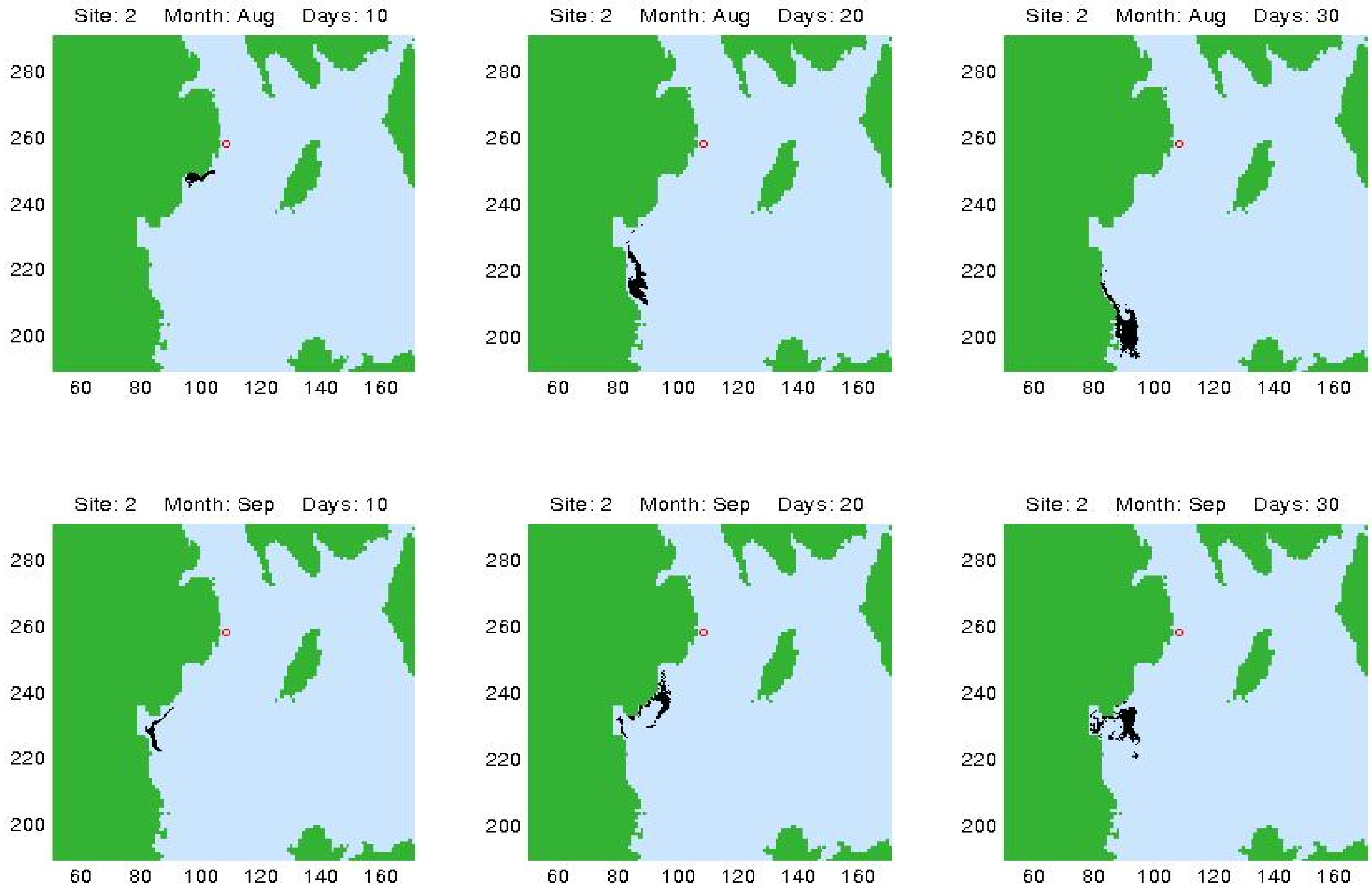
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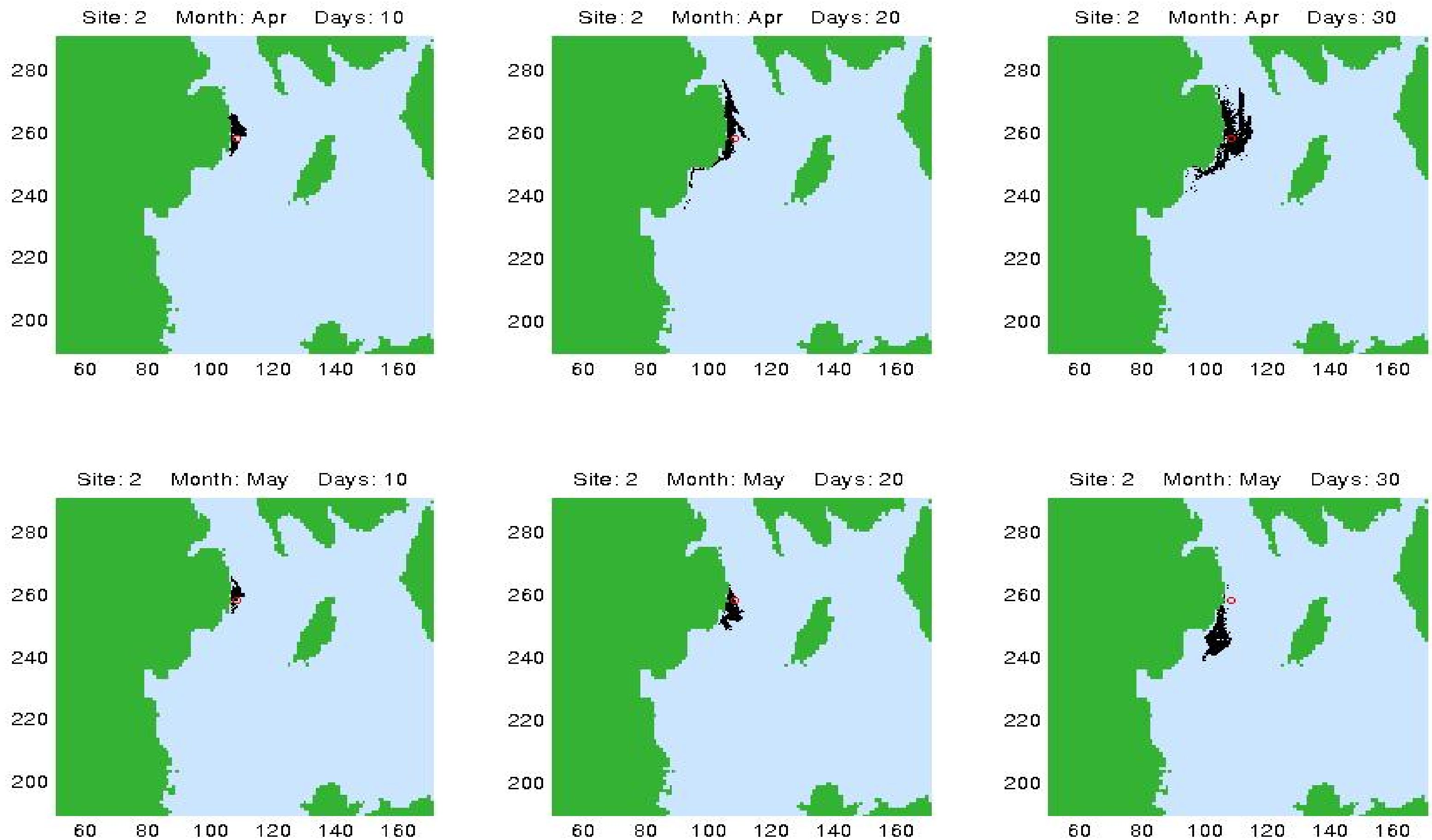
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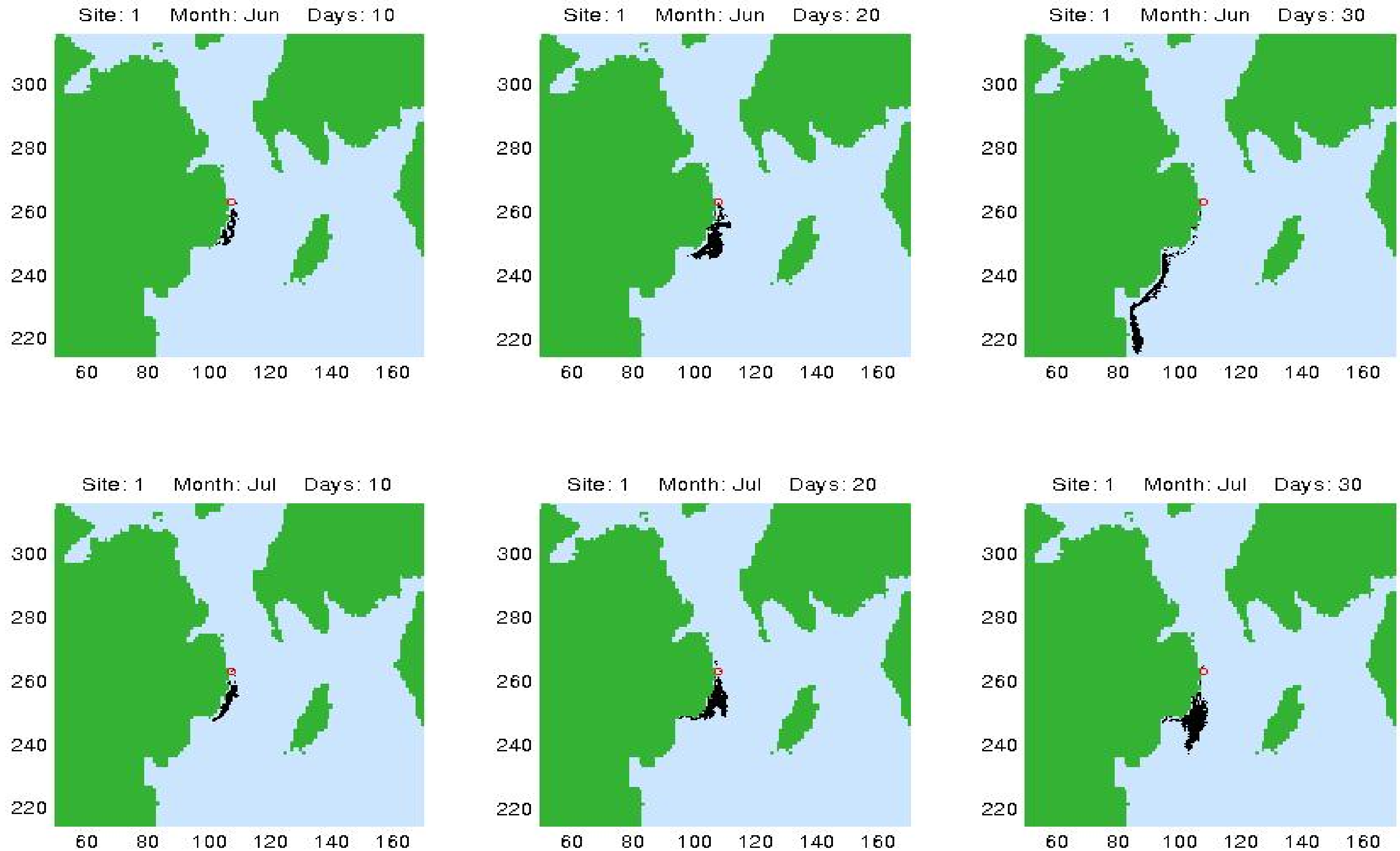
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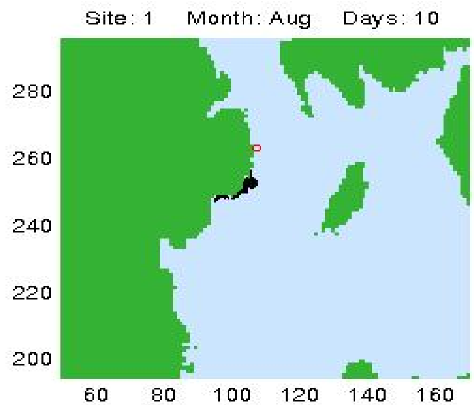
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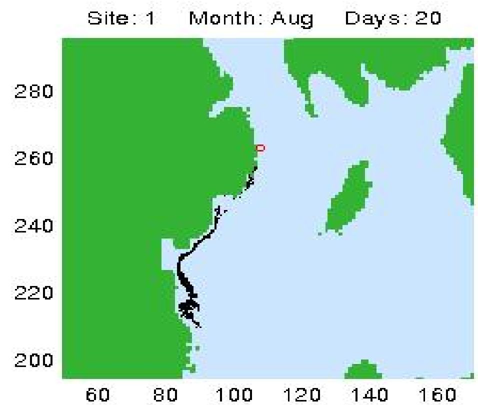
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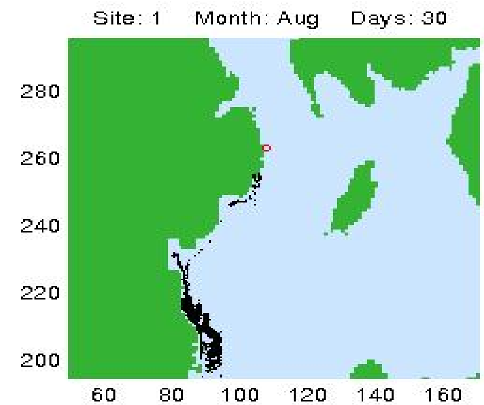
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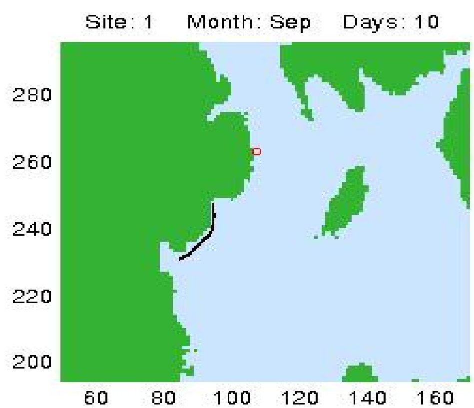
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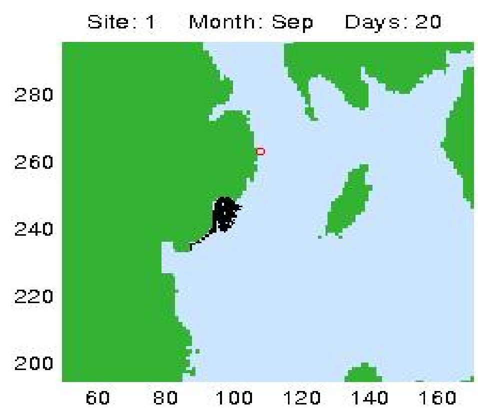
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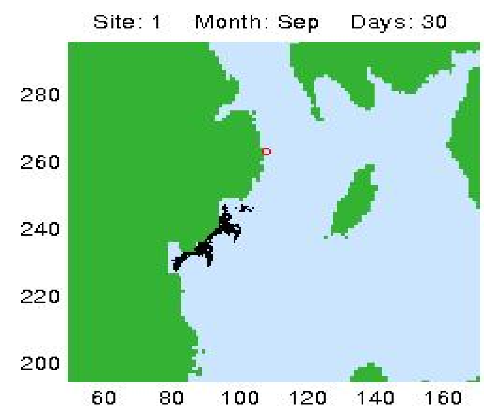
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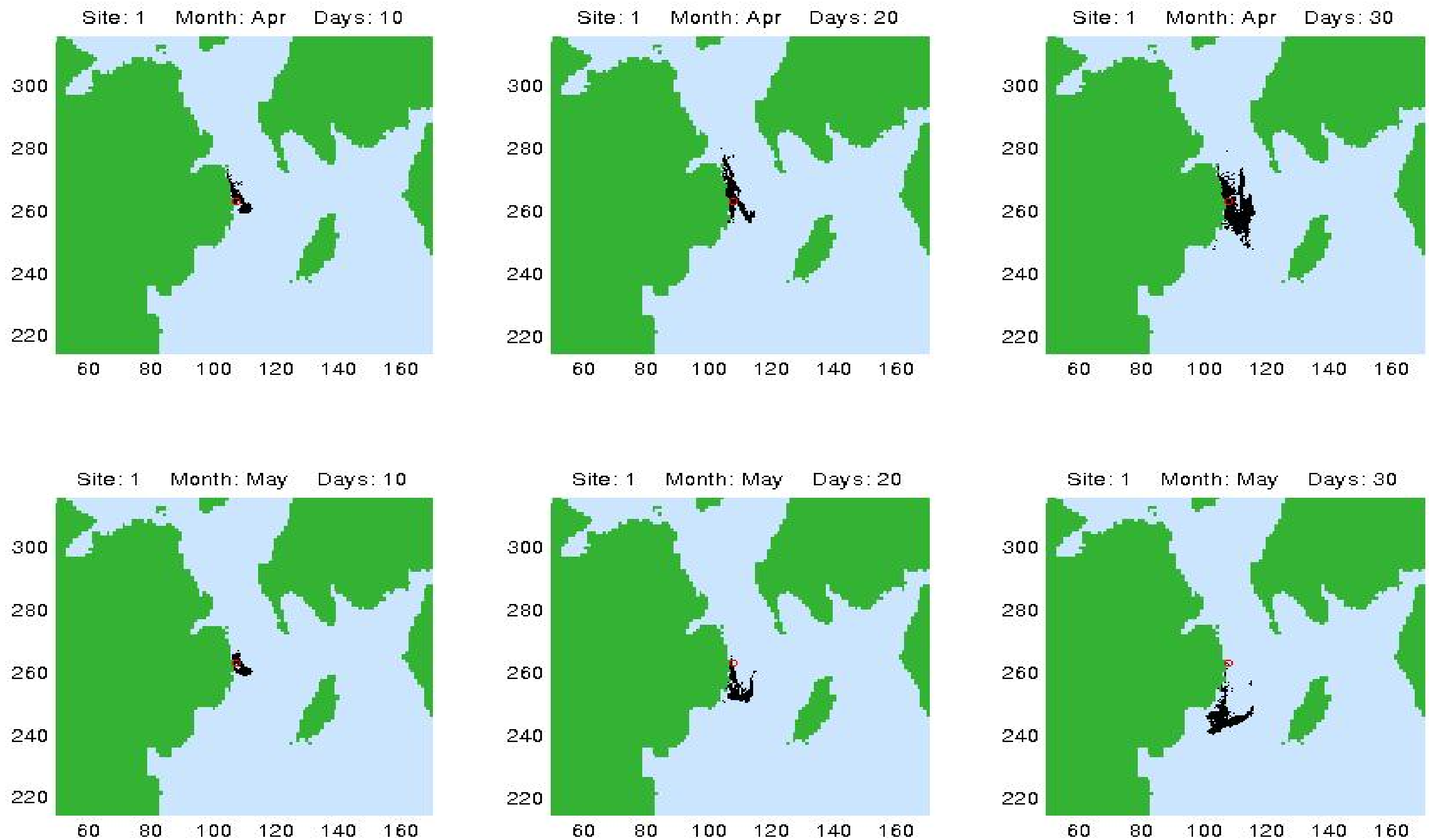
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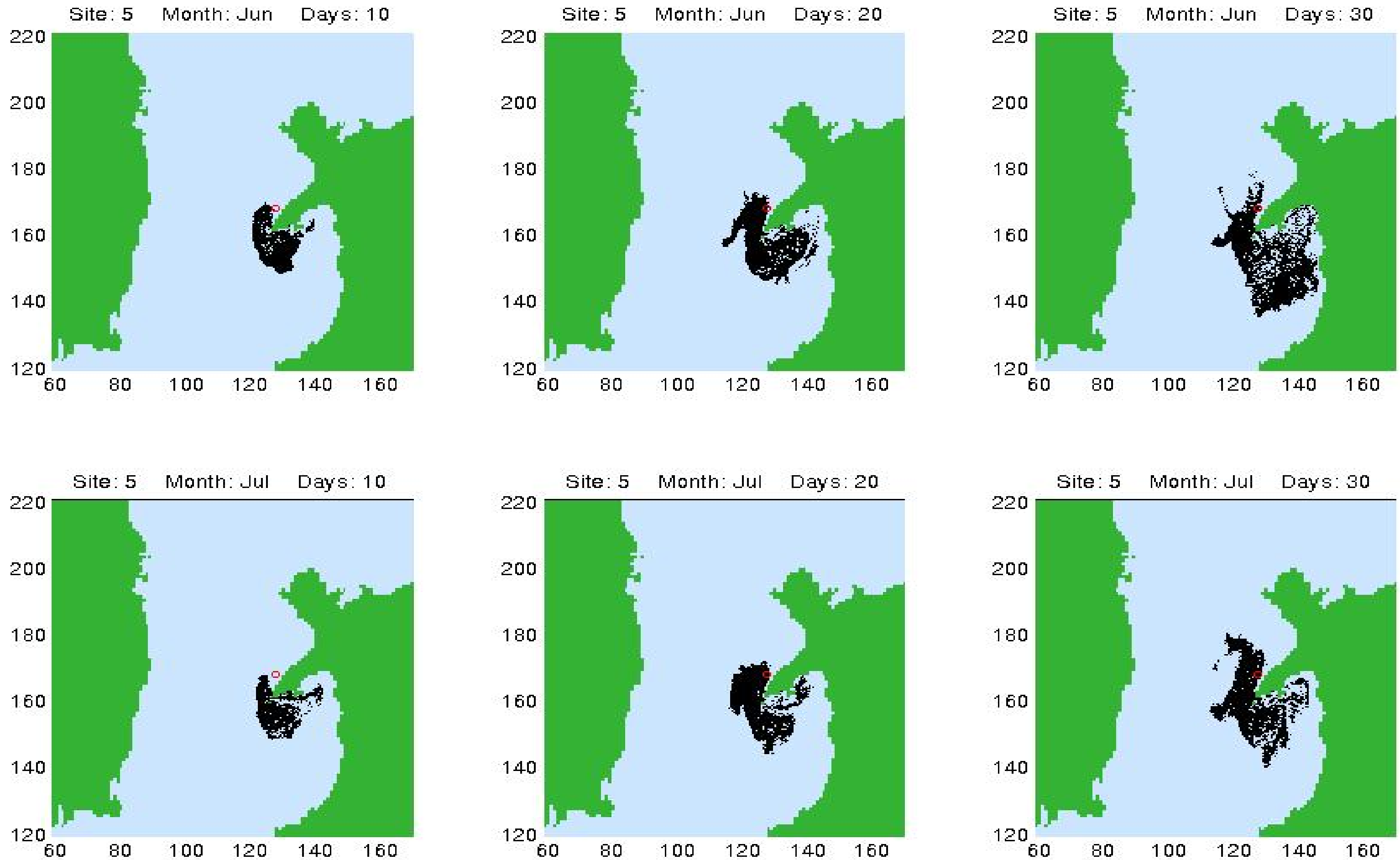
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